Prediction of Aerodynamic Coefficients and Analysis of Flow Past a Supersonic Missile

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ABSTRACT

This study is focused on application of CFD to evaluate the aerodynamic coefficients of tail controlled tactical missile configuration. Coefficients of lift, drag and pitching moment are calculated for a missile configuration and analyzed for supersonic speeds of Mach 2, 3 and 4 with angles of attack varying from -20° to +20°. Shock-wave formation, velocity and thermal boundary layers along with other qualitative aspects of flow field around the missile configuration are presented in detail. Missile DATCOM is also employed for calculation of aerodynamic coefficients for the same missile configuration. The comparative study of the two prediction techniques is presented. CFD post processing tools were employed to visualize the flow field around a supersonic missile under study. This research work can serve as a reference for aerodynamicists to evaluate the aerodynamic characteristics of similar designs.

Keywords: Aerodynamics coefficients; Aerodynamic design tools; CFD; Missile DATCOM

Nomenclature: C_L=Coefficient of Lift; C_D=Coefficient of Drag; C_M=Coefficient of Pitching Moment; α=Angle of Attack

INTRODUCTION

Missiles are high-speed weapons fitted with energetic materials to neutralize the moving or stationary targets. Modern missiles are equipped with sophisticated systems like guidance system, flight controls, turbo machinery and radar. The study of aerodynamic characteristics of missile configuration is an active research area of aerodynamics. Improvement in aerodynamic performance of missile configuration has always been a challenge for aerodynamicists. During the preliminary design phase of missile, it is considered helpful to carry out aerodynamic design optimization to meet the required design objectives. Design optimization employed during preliminary design phase, lead to better geometric shapes resulting in improved aerodynamic performance, low fuel consumption, long range, enhanced maneuverability and high speeds. Optimum aerodynamic shape is regarded as one that meets the highest performance criterions and fulfills the design constraints while being cost effective. Main aim of design optimization is to achieve maximum lift with minimum drag while enhancing the maneuverability of the missile. During the preliminary design phase, at each iteration of optimization process, various engineering design tools are employed for prediction of missile aerodynamic coefficients over a wide range of Mach No and Angles of Attack. This includes the calculation of coefficient of lift CL (or normal force coefficient CN), coefficient of drag CD (or axial force coefficient CA) and coefficient of pitching moment CM. Complete flight performance and stability characteristics of a missile can be described by these aerodynamic coefficients. Once detailed performance analysis and design optimization is completed during preliminary design; no major changes may be required in the aerodynamic parameters and missile shape during the later stages of design such as wind tunnel testing and prototype manufacturing phase.

To study the aerodynamic coefficients of missile configurations, various methods were adopted by the researchers and their details are available in literature. Most widely used techniques are the experimental methods, computational methods and empirical or semi-empirical engineering design tools (Figure 1). During the conceptual design phase of missile, empirical and semi empirical design tools like Missile DATCOM, Aero prediction code or Missile III are used. This software provide with quick yet less accurate estimation of aerodynamic coefficients. In the preliminary design phase computational techniques like CFD are generally employed to obtain more accurate values of aerodynamic coefficients.

When the preliminary calculations are completed and design phase further advances, the experimental design tools such as wind tunnel testing are employed to refine the preliminary calculations. Various scientists have used these experimental, computational and empirical methods to predict aerodynamic characteristics of missiles. Abney and Sooy used the experimental techniques (Wind Tunnel Testing) and empirical design tools (Missile DATCOM and Aeroprediction) for estimation of aerodynamic coefficients of missiles and compared the results of the two techniques [1,2]. A wide body of literature covers the application and comparison of experimental methods with the computational or numerical techniques for calculation of aerodynamic coefficients of various missile configurations [3-9]. Ridluan et al. studied the compressibility effects of flow over a missile by using computational and empirical techniques [10]. Maurice et al. and Rosema et al. draw comparison among all three approaches in their respective studies [11,12].

METHODOLOGY

The present study is focused on prediction of longitudinal aerodynamic coefficients for tail controlled tactical missile with body-wing-tail configuration as shown in Figure 2. Coefficient of lift CL, coefficient of drag CD and coefficient of pitching moment CM were calculated at supersonic Mach numbers of 2, 3 and 4 with angles of attack varying from -20° to +20° for each case. Two of the engineering design tools; Computational fluid dynamics (CFD) and Missile DATCOM were applied and results were validated by comparative analysis of aerodynamic coefficients obtained from both techniques (Table 1).

Calculation of aerodynamic coefficients of missile

In the present study commercial CFD solver ANSYS Fluent was used as a computational design tool and Missile DATCOM was used as an empirical engineering design tool. The flow chart of research methodology is shown in Figure 3.

Computational fluid dynamics (CFD) approach

The three dimensional CAD model of the conceptual design of the missile is imported in the design modeler of ANSYS Fluent for modelling the flow domain. The new reference axis is defined at the tail of the missile and circular sketch is plotted to extrude a cylindrical domain around the missile. The length of the domain is maintained at 15 times the length of the missile and similarly the diameter of the domain is kept 15 times the diameter of main body of missile. Then Boolean subtraction operation was applied with cylindrical domain as target body and missile as tool body, as shown in Figure 4.

Method; face sizing is set for meshing all the faces of the missile and inflation was applied to capture the boundary layer and shock wave formation at the surface of missile. The first layer height is set to be 0.001 m. Section view of fluid domain meshing around the missile body is shown in Figure 5. Very fine mesh is generated in the proximity of the missile body, to capture the rapidly changing flow parameters. It is not wise to generate very fine mesh in the entire fluid domain, because it will require lot of time and high computational cost. Hence coarse mesh is maintained at the outer edges of the domain where flow parameters are not expected to change very rapidly. Figure 6 shows the inflation, applied to generate very fine mesh elements near the missile body to capture the velocity and thermal boundary layers.

It is shown in Figure 4 that missile surface is designated as a solid wall, hence in ANSYS Fluent no-slip boundary conditions are applied at the missile surface. Pressure-far-field boundary conditions are applied at the cylindrical fluid domain enclosing the missile; at supersonic Mach numbers of 2, 3 and 4 and gauge pressure of 101325 pascal. x and y components of flow direction are varied according to variations in angles of attack (-20° to $+20^{\circ}$), temperature is set to 300 Kelvin. Density based; steady state, k-epsilon realizable turbulence model is applied to solve the fluid domain with energy on. Second order upwind, special discretization solution scheme is used with double precision. Ideal gas is used as fluid to calculate the aerodynamic coefficients for the missile configuration. Coefficient of lift C_L, coefficient of drag C_D and coefficient of pitching moment C_M are calculated with absolute convergence criteria at residual monitors' value of 0.0001. Solution initialization and reference values are computed from pressure- far-field.

Semi-empirical engineering approach

US Airforce Missile DATCOM is a semi-empirical engineering design tool that is used to compute the aerodynamic coefficients of missiles over a wide range of Mach numbers and angles of attack [13]. Missile DATCOM has been employed by many researchers to determine the aerodynamic characteristics of missiles [14-16]. This tool is frequently used during the preliminary design phase of missiles for aerodynamic shape optimization. It gives results quickly with adequate degree of accuracy for intelligent prediction of aerodynamic coefficients during conceptual design phase. In this study Missile DATCOM is employed to predict the aerodynamic coefficients of body-wing-tail configuration. The geometric data of the missile was given as input in the source file of missile DATCOM as shown in Figure 7. Flight conditions such as Mach number, altitude and angles of attack were also specified in the source code of the software.

RESULTS AND ANALYSIS

Aerodynamic coefficients at Mach 2

Aerodynamic coefficients of missile configuration are evaluated at Mach 2 with angles of attack varying from -20° to +20°. Two aerodynamic design tools Computational Fluid Dynamics (CFD) and Missile DATCOM are employed; values of aerodynamic coefficients obtained from both the techniques are tabulated in Table 2. The graphs of Coefficients of Lift (C_L) vs angles of attack (α), Coefficient of drag (C_D) vs angles of attack (α) and Coefficient of pitching moment (C_M) vs angles of attack (α) are shown in Figures 8-10 respectively. The graphs are plotted to show the values of aerodynamic coefficients obtained from CFD and Missile DATCOM on the same graph for visual understanding and comparison between two techniques (Table 2).

Figure 8 shows the dependence of lift coefficient on angles of attack at constant Mach number. As the incidence angle increases the coefficient of lift also increases and coefficient of lift decreases with decreasing angles of attack. Consistent results are obtained from the two techniques. CFD results are very close to the Missile DATCOM values at small angles of attack whereas at high angles of attack (above 10°) the percent difference in the results of two techniques increases. Overall trend lines are same for coefficient of lift obtained from the two methods. For negative angles of attack, coefficients of lift are also negative and increase with increasing negative values of incidence angles.

Figure 9 shows the dependence of drag coefficient on the angles of attack at constant Mach number. The drag coefficient increases with increasing values of angles of attack for both positive and negative values of incidence angles. Trend of the drag coefficient values obtained from CFD and Missile DATCOM is coherent. For both cases CFD and Missile DATCOM smooth rise in values of C_D is observed for small values of α (from 0° to ± 10°). Whereas very sharp increase in values of C_D is observed with increase in α, beyond 10° of flow incidence angle. This is a logical trend as more drag is experienced by the flow around the missile at higher incidence angles.

Figure 10 shows the variation of pitching moment coefficient of the missile configuration with varying angles of attack at constant Mach number. Calculated values of pitching moment coefficients are positive for negative values of incidence angles and are negative for positive values of incidence angles. The absolute value of pitching moment coefficient increases with increasing angles of attack. The values of pitching moment coefficient obtained from both Missile DATCOM and ASYS Fluent were found to be consistent with each other. Similar trend is shown by the graphs of pitching moment vs angles of attack for both the techniques.

Figure 11 shows a very useful flow visualization method that can be realized in ANSYS Fluent, it is the generation of pathlines of fluid flow around the missile body. In this figure fluid flow at the positive incidence angle of 10° and Mach 2 is visualized around the missile configuration under study. Figure 12 shows the contours of pressure at positive 10° angle of attack and Mach 2. The formation of oblique shock waves at the nose and fins of the missile can be seen. The sharp pressure variations occur across the shock waves. Velocity decreases across the oblique shock wave and resultantly the pressure increases. This sudden rise in pressure across the oblique shock waves can be seen in Figure 12. Shock wave formation and numerous other qualitative aspects of the flow can be studied in CFD post processing of ANSYS Fluent. It is worth mentioning that at positive incidence angles weak oblique shockwave is formed at the upper side of missile nose cone and very strong shock wave is formed at the lower side of the nose cone. Strong shock at the lower side of missile results in sharp drop in velocity and sharp rise in pressure. Weak shock wave on the upper side of missile does not cause much drop in flow velocity and flow downstream the shock remains at higher velocities and lower pressure. This explains the existence of high pressure at the lower side and lower pressure at the upper side of missile. This pressure variation results in

Figure 13 shows the velocity contour around the missile configuration at the plane of symmetry, at positive 10° angle of attack and Mach 2. The no slip condition exists at the surface of the missile hence the missile surface the flow velocity is zero. In the very short region known as the velocity boundary layer, the flow velocity sharply increases from zero at the missile surface to the free stream velocity at the outer edge of boundary layer. This small region of velocity boundary layer is visible in Figure 13. At the lower side of nose cone strong oblique shock wave is formed and velocity sharply decreases across the shock, whereas at the upper side of nose cone very weak oblique shock wave is formed at positive 10° angle of attack, hence velocity does not drop considerably across the shock and flow velocity remain high downstream the shock on upper side of missile. On the lower side of missile, strong oblique shock waves formation results in the region of low velocity.

Aerodynamic coefficients at Mach 3

The aerodynamic coefficients were evaluated at Mach 3 for the missile configuration under study at angles of attack varying from -20° to +20°. Two aerodynamic design tools were used for prediction of aerodynamic coefficients: Computation Fluid Dynamics and Missile DATCOM. The coefficient of lift CL, coefficient of drag CD and coefficient of pitching moment CM were evaluated by ANSYS Fluent and Missile DATCOM. Calculated values of aerodynamic coefficients are shown in the Table 3. The graphs of aerodynamic coefficients vs angles of attack at Mach 3 are plotted and shown in Figures 14-16. The values of aerodynamic coefficients obtained from both the engineering design tools (CFD and Missile DATCOM) are plotted on the same graph for each of the coefficient of lift CL, coefficient of drag CD and coefficient of pitching moment CM against varying angles of attack (α), from -20° to +20°. This approach helps to draw comparison between the values obtained from CFD and Missile DATCOM, immediately.

Figure 14 shows the variation in the lift coefficient CL with varying angles of attack at constant speed of Mach 3. The similar trend in the values of lift coefficient is seen with varying angles of attack as it was observed for Mach 2, but the values are different (dependence of CL on Mach number at constant incidence angles will be discussed in following sections). The coefficient of lift CL was observed to increase with increasing angles of attack and decrease with decrease in angles of attack. The values of Missile DATCOM and CFD are very close at smaller angles of attack (-10° to +10°). However, the difference in the values of CL obtained from two techniques increases at higher angles of attack (beyond ±10°). The overall trend of the dependence of coefficient of lift CL on angles of attack is similar for the results of DATCOM and CFD.

Figure 15 shows the dependence of drag coefficient CD on the incidence angle α, that varies from -20° to +20° at Mach 3. The values of drag coefficient CD increases with increase in angles of attack. For smaller angles of attack, less than 10° there is a smooth increase in the value of CD with increase in α. However, for higher angles of attack, above 10° sharp increase is observed in the CD values for increasing angles of attack α. The trend of CD variation with α is found to be consistent for the values calculated from the two aerodynamic design tools, CFD and Missile DATCOM.

Figure 16 shows the variation of pitching moment coefficient CM for the changing angles of incidence α, values of α varies from -20° to +20° at Mach 3. Positive values for coefficient of pitching moment are observed for negative angles of attack and negative values of pitching moment coefficient were observed for positive angles of attack. For values of pitching moment coefficient obtained from both the Missile DATCOM and CFD; an increase in angle of attack cause an increase in the values of pitching moment coefficient CM. The general trend of the CM values obtained from the CFD and Missile DATCOM were found to be coherent with each other.

Figure 17 illustrates the flow visualization technique of ANSYS Fluent where pathlines of the flow field around the missile are drawn to visualize the interaction of high speed fluid with the missile body. Flow pattern around the missile body, winglets and tail fin can be visualized and studied in detail.

Figure 18 illustrates the pressure contours at the plane of symmetry of the missile. At supersonic speed of Mach 3 the oblique shock waves are formed. The case shown here is at positive incidence angle of 10° hence a very strong oblique shock wave forms at the lower side of nose cone and pressure increases across the shock. At the lower side of the missile as the flow past the nose shock wave it interacts with the winglets and tail fin, strong oblique shock waves are generated at winglets and tail fin that can be seen in Figure 18. This results in region of high pressure at the lower side of the missile. On the upper side of the nose cone at positive incidence angle of 10° and Mach 3, a comparatively weak shock wave is observed; pressure increase across the shock and the pressure rise can be seen in the Figure 18. But at the upper side of missile, flow downstream the nose shock is not attached with the missile body due to boundary layer separation at positive 10° α. Therefore, strong shock waves do not form on the upper side of missile at the winglet and tail-fin. This results in the low pressure region on the upper side of the missile. The low Figure 19 shows the velocity contours on the plane of symmetry of the missile at positive incidence angle of 10° and at Mach 3. The no-slip boundary conditions exist at the missile body and zero velocity of the flow can be seen on the missile body. In the very small region, the velocity abruptly changes from zero at the wall to free stream velocity. This small region of flow is called as the velocity boundary layer. The velocity boundary layer can be seen in Figure 19. Like the pressure contour, the velocity contour also illustrates the formation oblique shock waves at the nose cone of the missile. Velocity decreases across the oblique shock waves. This decrease in velocity is visible in Figure 19. Decrease in velocity is more pronounced at the lower side of nose cone, corresponding to a strong oblique shock wave. Velocity decrease is not very prominent on the upper side of nose cone, as it corresponds to the weak oblique shock wave. This results in the region of high velocity on the upper side of missile and low velocity region on the lower side of missile.

Aerodynamic coefficients at Mach 4

All the aerodynamic coefficients are calculated for the missile configuration under study, at Mach 4 with varying angles of attack. Angles of attack vary from -20° to +20°. Coefficient of lift C_L, coefficient of drag C_D and coefficient of pitching moment C_M were calculated, using the two aerodynamic design tools: Missile DATCOM and ANSYS Fluent. The estimated values of aerodynamic coefficients are tabulated in Table 4. The graphs of aerodynamic coefficients with respect to varying angles of attack are formulated and presented in Figures 20-22, for C_L vs α, C_D vs α and C_M vs α, respectively. The values of aerodynamic coefficients obtained from CFD and Missile DATCOM are plotted on the same graph to give a comparison of the values immediately.

Figure 20 shows the variation of coefficient of lift C_L with variation in the angle of attack at Mach 4. Angles of attack vary from -20° to +20°. The results of CFD and Missile DATCOM plotted on a graph in Figure 20, shows that the values obtained from both the aerodynamic design tools are consistent with each other. The coefficient of lift increases with the increase in angle of attack and decreases with the decrease in angle of attack. The values of lift coefficient calculated from CFD match closely with the results of Missile DATCOM at low angles of attack (less than ±10°), but the difference in the values increases at higher values of angles of attack (beyond ±10°).

Figure 21 shows the variation of drag coefficient with varying angles of attack, from -20° to +20° at Mach 4. The results of CFD and Missile DATCOM are plotted on the same graph and are found to be consistent with each other. The trend of variation in the values of C_D for changing angles of attack was observed to be same for CFD and Missile DATCOM. The values of C_D increase with increase in angles of attack and decreases with the decreasing angle of attack. The rise in the C_D values is found to be smooth for lower range of angles of attack (below ±10°) whereas at higher angles of attack (beyond ± 10°), C_D drastically increases. This is logical as more drag is experienced by the supersonic flow as the incidence angle increases.

Figure 22 shows the variation of pitching moment coefficient with the varying angles of attack, -20° to +20°. The results of CFD and Missile DATCOM are plotted on the same graph for comparison, the values from both the aerodynamic design tools show consistency with each other and overall trend of values is found to be same. The pitching moment coefficient (C_M) values are negative for positive angles of attack and are positive for negative angles of attack. Absolute value of pitching moment coefficient observed to increase with increasing angle of attack for both positive and negative angles of attack.

Figure 23 provides with visualization of flow past the missile at supersonic speed of Mach 4 and +10° angle of incidence. The pathlines of the flow are generated around the missile body, winglets and tail-fins.

The pressure contour at the plane of symmetry of the missile is shown at +10° angle of attack and Mach 4 in Figure 24. At Mach 4 and incidence angle of +10° very strong oblique shock wave is formed at the lower side of nose cone, winglets and tail-fins. The pressure increases across the shock waves, this pressure rise can be seen in Figure 24 on the lower side of the missile. This results in a region of very high pressure at the lower side of missile. On the upper side of nose cone a weak shock wave is formed and pressure rise across the weak shock wave can be seen in the Figure 24. Flow downstream this weak shock wave does not remain attached to the missile body due to +10° incidence angle, hence the flow velocity remains high on the upper side of missile and this results in a region of low pressure. This explains the rise in the values of coefficient of lift at positive incidence angles. The phenomena are same but in opposite direction for the negative values of angles of attack.

Velocity at the missile surface is zero. Velocity increases from zero to free stream value in a very thin region of flow near the missile surface; this region is known as velocity boundary layer. The formation of strong oblique shock waves at the lower side of missile can be seen in Figure 25. The velocity decreases across the oblique shock waves, hence the flow at lower side of missile forms the region of low velocity. On the upper side of missile, a weak oblique shock wave is formed at +10° angle of attack. The velocity drop across this weak oblique shock wave is not very significant; hence the downstream flow remains at high velocity. This results in the region of high velocity on the upper side of missile. The velocity boundary layer separates, on the upper side of missile body, at the positive incidence angles. This boundary layer separation can be seen in Figure 25. Velocity contours at the plane of symmetry of the missile are shown in Figure 25 at +10° incidence angles and Mach 4.

Some qualitative aspects of flow past supersonic missile

Various post processing tools of ANSYS Fluent can be employed to analyze the aerodynamic characteristics of flow past a supersonic missile. The shock waves are the cause of abrupt changes in the flow parameters at supersonic speeds. The study of these shock waves and determination of the region of flow under the influence of shock wave is one of the key goals of aerodynamic analysis. For the present case study, the oblique shock waves formation at the nose of missile at supersonic speeds is studied in detail using CFD post processing tools. The angle of attack was fixed at +10° and velocity contours on the pane of symmetry of missile are displayed at varying Mach numbers. Refer Figure 26 the first case shows the oblique shock wave at +10° angle of attack and Mach 2. The angle of oblique shock wave is very large in this case, but the shock waves are not very strong. At Mach 3 with same incidence angle of +10° the comparatively stronger oblique shock waves are formed with smaller shock wave angles. At Mach 4 with the same incidence angle of +10° very strong oblique shock waves are formed with very small shock wave angles.

Figures 27 and 28 shows the velocity and thermal boundary layers on the surface of missile at supersonic speed of Mach 3 and angle of incidence of zero degrees. The velocity streamlines and variation of velocity across the oblique shock waves at the nose cone can also be seen in the Figure 27. Likewise, the temperature variation across the shock wave at the nose cone is shown in Figure 28.

DISCUSSION AND CONCLUSION

During the conceptual and preliminary design phases of missile it is helpful to correctly estimate the aerodynamic coefficients such as coefficient of lift C_L, coefficient of drag C_D and coefficient of pitching moment C_M. Prediction of these aerodynamic coefficients allows to study the aerodynamic characteristics of particular missile shape and help in design optimization, to achieve required design objectives. Three most employed engineering tools to determine the aerodynamic coefficients are: wind tunnel testing of scale down model, computational or numerical analysis and use of empirical or semi empirical design tools. In the present study computational and empirical methods were used to estimate the aerodynamic coefficients of supersonic missile configuration. CFD solver, ANSYS Fluent and empirical design tool, Missile DATCOM are used. Aerodynamic coefficients are calculated and results of two approaches are compared by plotting the graphs of C_L vs α, C_D vs α and C_M vs α at three different supersonic Mach numbers (Mach 2, 3 and 4). The results of CFD and Missile DATCOM are found to be consistent with each other. Coefficient of lift C_L increases with increase in angle of attack α. Values of C_L obtained from CFD and Missile DATCOM was very close for smaller angles of attack (less than ±10°), for large values of angles of attack (beyond ±10°) the difference in the values increases. Coefficient of drag increases smoothly at smaller angles of attack (less than ±10°) for increase in α, for both positive and negative values of α. But rise in C_D values with increase in angles of attack was very sharp at higher values of α (beyond ±10°). Values of C_D obtained from CFD were slightly higher than those obtained from Missile DATCOM at all three Mach numbers. Negative values of coefficient of moment C_M are obtained for positive angles of attack and positive values were obtained for negative angles of attack. Absolute value of C_M increases with increase in α for both positive and negative angles of attack. Oblique shock wave formation, pressure and velocity variations, shock wave angles, velocity and thermal boundary layer and related qualitative aspects of flow past supersonic missile are presented in detail. The oblique shock wave angle decreases with increase in Mach number at constant angle of attack. The velocity boundary layer separation occurs on upper side of missile for positive angles of attack. At positive incidence angles strong oblique shockwave forms at the lower side of nose cone and weak oblique shockwave forms on the upper side of nose cone. This results in the region of low pressure and high velocity at upper side of missile body and a region of high pressure and low velocity on the lower side of missile body. Pressure, velocity and temperature variations across the shockwaves are presented at varying Mach numbers and angles of attack. Velocity decreases while temperature and pressure increase across the oblique shock waves. This study can serve as a reference for analysis of similar missile configurations.