Aerodynamic performance enhancement of missile using numerical techniques

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Abstract
The objective of the paper is to conduct aerodynamic analysis on V-2 missile. The V-2 missile was the world’s first ballistic missile and the first object to go into space. It is a long-range liquid propelled missile. It uses aerodynamic surfaces such as wings, fins, control surfaces and fuselage to deliver the lateral maneuverability. This is accomplished by deflecting the control surfaces through the actuation mechanism and thereby modifying the equilibrium forces and producing various moments. The V-2 missile was 14 meters long and weighed 12,700 – 13,200 kg at launching. It produces about 266 KN of thrust.

ANSYS modeler is used to model the V-2 missile, and the flow around the missile body has been evaluated using the ANSYS workbench. This paper carried out simulations for varying angles of attack and Mach numbers until the stall was observed. Effects due to density, pressure coefficient, temperature and Mach number on the missile is noted in order to undergo detailed flow analysis.

Keywords: V-2 Missile, Aerodynamic configuration, Flow analysis, ANSYS Software

1. INTRODUCTION

The missile, a rocket or jet engine powered weapon designed to transport a payload, usually a volatile warhead with precision at high velocities to a predetermined destination or target[15,16]. Most of the warheads have an advanced guidance system courtesy of which they are commonly referred to as guided missiles. Here, the German V2 missile[18] (figure 1) was modeled to run the simulations and carry out the results. The study of the aerodynamics of a missile is vital has it deals with the accuracy of the control and guidance systems that can accomplish the desired mission[9,10]. Most of the aerodynamics is studied by numerical analysis of the flow. Selection towards an optimum missile performance is aided by aerodynamic properties of various external components and their configuration along with lift and drag characteristics and aerodynamic stability[10]. Higher the angle of attack, the higher the lift is acting on the body. Therefore, affecting the stability of the missile. The airflow is characterized by properties such as pressure, velocity, temperature, density etc.

They play an essential part in classifying the missile’s state of performance and these properties are calculated using equations such as energy, momentum and Sutherland equations.
2. Literature review

Zhang Wen-Dian et al. [1] studied the aerodynamics of a theater Ballistic Missile with an “x+” finned configuration by cross verifying it over three methods of calculation viz. theoretical, experimental and numerical. For the computational analysis, ANSYS Fluent software was used by creating a geometric model up to a scale. Using the German V2 missile as reference, Spalart-Allmaras model has been applied due to which mean flow quantities have been resolved in the paper. Meshing was done stage wise using sub-models. The flow analysis through the model was calculated longitudinally. The solutions for energy, turbulent viscosity, mass and momentum was obtained when the solution converged with less than 0.5% change after the last 100 iterations. The MISSILE DATCOM was used to calculate the center of pressure, aerodynamic forces and moment at numerous functioning conditions for primary configuration using the semi-empirical method. It gave reasonable aerodynamic coefficient predictions. A supersonic wind tunnel with a Mach range of 0.3 – 4.5 was used to obtain the result with the help of a detailed stage model which was 1:10 scale in nature.

Nenad Vidanovic et al. [2], aimed to establish an efficient fin design through numerical optimization techniques while considering fluid and structural interactions. The computational method was used to analyse the fluid structure interactions through a domain that was closely coupled. This was done to a very high degree of accuracy and reliability. The short-range missile fin structure was analysed by the numerical optimization procedure. An embedded surrogate based evolutionary optimizer drives the single level method which is the multidisciplinary feasible method proposed in this paper. There was an enlarged number of geometries of fin as a result of improved algorithm. It’s distinct feature was the complete enhancement of geometry of the missile with decrease of cost and possessions. A challenging task that was faced by this group was to get rid of scaling between real fin geometry model, which was used for the static structural test and the existing wind tunnel missile model geometry, which was used for aerodynamic testing.

Sebastian Marian ZAHARIA et al. [3] studied a missile of stringer type with cylindrical fuselage containing 10 control surfaces, out of which, 8 are directional surfaces to carry out turns and the remaining 2 are used to execute maneuvers for changing the angle of attack of the testing missile. Other than the controlling surfaces, the missile also is equipped with 4 directional stabilizers. The CFD simulation conducted in this paper was carried out on a missile with a ballistic missile geometry; however it was equipped with a new structure for determining the flight performance and aerodynamic...
configuration. For structural analysis, finite element method was used, which in turn allowed to precisely determine the areas on the geometry where the stress and strain were the greatest which in turn helped to determine the points on the geometry to increase its structural integrity. In order to protect it against temperature and pressure, thereby increasing its reliability.

Mohammed Abdul Hameed Khan et al. [4]. Aimed to research aerodynamic and structural analysis of the Tomahawk Missile. The reason for carrying out this experiment is to determine the best-suited nose cones, namely conical, elliptical and Von Karman O. The aerodynamic analysis will be carried on three different mach numbers at subsonic supersonic and hypersonic velocities. The Research was conducted using CAD tools, namely Creo 4.0 for modeling the missile and its different nose geometry. ANSYS was used for structural and fluid analysis. For structural analysis of the nose, varying materials namely aluminum, titanium, and structural steel were used in the analysis process. The conclusion was that structural steel then aluminum could be the well-suited material.

G. Martynenko et al. [5] studied the breakage of a missile through numerical simulations. The design of the missile basic units is treated. ANSYS was used to run the highly detailed simulations. This method has three stages. (I). Analyzing the static stress-strain of the missile formed due to the assembly process, (II). The active stress state of the missile calculations, (III). In the most loaded units, dynamic fracture was analysed. The limitations of the missile are selected in command of a rupture to take place in a structure specified range. In this method, the dynamic fracture of the missile was simulated by providing sufficient impact pressure and it is calculated using the above mentioned 3 stage method. As a outcome of this breakage analysis, the diameter of the tension buckle pin, is determined when it is broken. It is obtained the following fracture time: \( t = 1.8 \times 10^{-3} \) s. On comparing this end result with the experimental result, It is concluded that the outcomes are very similar.

3. Methodology

The flow over the V-2 missile has been simulated using ANSYS Software in which the model is designed [1,6]. Farfield is created around the missile and meshing was done to make the model efficient for simulation and flow analysis is conducted after the simulation is converged. Validation and verification are required to evaluate the precision of the solution by comparing it to the results known. The importance of validation is quite a lot as it increases the accuracy and thereby providing good results. Validation has been done for various parameters (such as velocity, pressure, temperature, density, coefficient of pressure) obtained from the simulation with the known values. A model of V-2 missile is created using ANSYS modeler with the dimensions as shown in the figure 2[1].

![Figure 2. Schematics of the V-2 missile](image)

Fluent meshing tool is used to provide the mesh around the body. Fine meshes around the missile are designed using refinement.(i.e., divides the whole component into finite no. of small elements) thereby improving the quality of the mesh and makes sure it is efficient for simulation. The mesh preview is shown in figure 3.
Grid independence check was also done for the designed model by changing the degree of the meshes. It was seen that changes in element size resulted in a converged solution and this check was carried out by varying the size of element in between $5 \times 10^4$ to $8 \times 10^4$ and the variation in velocity is plotted as shown in figure 4.

A density solver is used to calculate the solution as the flow is supersonic. From all the turbulence models, Spalart-Allmaras was chosen. The computational power is very low as it uses only one turbulence equation. This model was developed for the missile body. Convergence plot values were very reliable. In the boundary conditions, the outer walls of the fluid domain were chosen as pressure-far-field with Mach number as 2 and angle of attack to be zero. The initial pressure was considered to be 23424.3 Pa. The walls of the missile body were chosen as wall boundary conditions with full resolution. The solution converged before 200 iterations with residuals of $10^{-6}$ as shown in figure 4. After successful completion, the Flowfield over missile has been identified using CFD, which gives a better understanding of the flow over the body. The contours shown below in figure 5.1 to 5.4 are of density, pressure coefficient, static temp and Mach number at the boundary conditions stated earlier. As the results suggest, the error is less than 5%, with which we can conclude the accuracy of the design.

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**Figure 3.** 2D Meshing of missile

**Figure 4.** Grid independence check

**Figure 5.1 :** Contours of temperature at $\alpha = 0^\circ$

**Figure 5.2 :** Contours of density at $\alpha = 0^\circ$
The missile flies at mach 2 and the fluid (air) which meets this body, separates due to the formation of drag on the missile body which in other terms called flow separation. This drag is formed due to the presence of primary control systems. At zero angle of attack, it is seen that there is equal distribution of shock waves at the top and bottom surfaces of the body as shown in the contours. As the velocity is not too high at a low angle of attacks (mach=2), fluid particles doesn’t present higher energy exchange compared to higher speed. Therefore, friction at the surface of the missile is not very intense at low mach number. It is also observed that static temperature is high on the bottom of the missile compared to the top surface which resulted in higher speed on the top surface. Therefore, It can be stated that areas with high static temperature as the least Mach number.

At a higher angle of attack, the flow separates irregularly as shown in the figure 6.3. Therefore, drag on the below surface is much higher than that of the upper surface of the missile which results in more friction on the below surface and it is seen that temperature and density is maximum near the bottom fin and the velocity is maximum. The minimum velocity is recorded behind the missile. On further increasing the angle of attack to 16 degrees, it is observed that there is a significant separation of flow resulting in shock formation with maximum value of pressure on the downside of the fins with very high friction and drag. Therefore, it is observed that, with increase in the angle of attack, the friction and drag increases significantly compared to the upper surface.
4. Results and Discussion

The paper carried out CFD simulations and finite element analysis to understand the aerodynamic performance of the ballistic missile and determining the parameters (density, static temperature, pressure coefficient, mach number) by changing the $\alpha$ from 0 to 16 degrees (figure 6.1 to 6.4) by keeping the initial pressure constant and comparing it with the theoretical values. They were represented by the airflow path around the body. The value of the pressure coefficient decreases due to the generation of shock waves by the body contour, on increasing the angle of attack. Similarly, there will be a change in the magnitude of Mach number, density and static temperature. This variation is shown in the graphs below (figure 7.1 to 7.4).

**Figure 6.3:** Coefficient of pressure at $\alpha = 12^\circ$

**Figure 6.4:** Coefficient of pressure at $\alpha = 16^\circ$

**Figure 7.1.** Graphical variation of Mach number with $\alpha$

**Figure 7.2.** Graphical variation of Static temperature with $\alpha$
5. Conclusions

A ballistic missile was modeled and numerically analyzed as mentioned earlier with accurate dimensions [1]. A suitable pressure far-field is designed around the missile and the process of meshing was done to divide the farfield into small elements. A CFD simulation was then carried out using ANSYS software on the model for determining the missile performance and the aerodynamic configuration in a 2-dimensional plane. A finite element analysis is performed and the results obtained allowed to precisely determine the flow over the body. The Fluent analysis has been conducted for mach number ranging from 2 – 3.5 at angles of attack varying between 0 to 16°. The design of the ballistic missile used for the meticulous analysis enables it to have a center of gravity near the nose and center of pressure nearer the fin. Through the varying aerodynamic condition, the pressure coefficient is not affected much, due to which even at a high angle of attack, the aerodynamic efficiency of the missile is maintained to the extent that sustainable flight is possible at high velocities. From the graphs, we can safely conclude that with the increase in the α, the air density over the missile remains more or less the same, the Cp decreases, temperature increases along with the pressure on the bottom surface of the missile resulting in higher drag and friction. There is no Karman vortex street formed and the nose is subjected to the most extreme condition.

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