Design and Analysis of Hypersonic Aircraft with Transonic and Supersonic Fluid Flow analysis

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Abstract— This paper aims to design new geometry for hypersonic aircraft along with a study of transonic and supersonic fluid flows over Northrop B-2, Lockheed F-22 respectively. The hypersonic aircraft uses the Waverider concept in its design. Specific parameters (like drag coefficient, lift coefficient, pressure, and velocity variation) that effect aerodynamic efficiency are studied. Finite volume methods (FVM) of computational fluid dynamics (CFD) with the help of cartesian based meshes are used in determining these parameters. The structured cartesian immersed – body mesh with rectangular cells (cuboids) are used. The geometry of aircraft is created using Solidworks and CFD analysis is carried out using Solidworks Flow Simulation. The stated parameters for different aircraft are compared.

Key words: Coefficient of Drag, Coefficient of Lift, CFD, FVM, Hypersonic Aircraft

I. INTRODUCTION

In this era of rapid advancement in technologies, every country has its own contribution to the development of aircraft and missiles that are capable of traveling more than five times the speed of sound. These capabilities increase the military power of a country. Globalization has increased the need for everyone to travel across the globe in less time possible. So this raised a need for the development of civilian aircraft that can travel at high speed and are safe. The complexity in the design of geometry and selection of materials for the manufacturing of aircraft are limited. So the research and development in this area have a vital role in the development of better and safe aircraft with increased efficiencies. This paper will provide a new design of hypersonic aircraft.

A supersonic aircraft flies faster than the speed of sound (Mach 1) i.e., 412–1,715 m/s or 1,482–6,174 km/h. Hypersonic speeds are generally referred to speeds above Mach 5 (1,715–3,430 m/s or 6,174–12,348 km/h). The given values of flight are taken in the dry air of a temperature of 20°C. Transonic refers to the condition of flight in which a range of velocities of airflow exist in the range of Mach 0.8 to 1.0, i.e. 988–1,482 km/h (274–412 m/s) at sea level.

A waverider is a hypersonic aircraft design which uses shock waves to produce lift, in addition, to lift of the aircraft due to a phenomenon is known as compression lift. A cone flow waveriders is used in the design of present hypersonic aircraft.

II. GEOMETRY OF HPERSONIC AIRCRAFT

The four standard views of hypersonic aircraft are as shown in Figure 1.

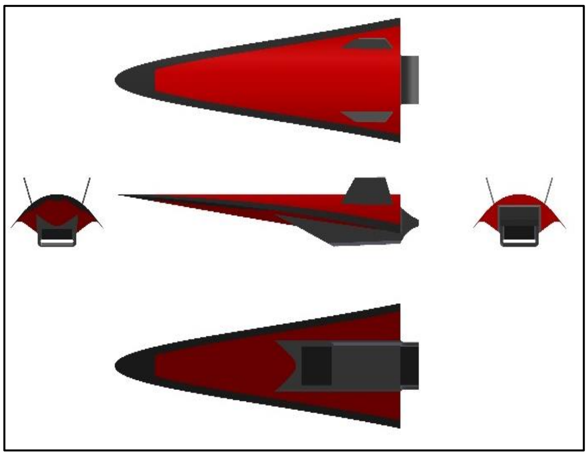

Fig. 1:

The hypersonic aircraft is analyzed by using Solidworks Flow Simulation for 0, 5, 10, 15, 20, 25 angles of attack measured in degrees at altitudes of 12000 m, 15000 m, 18000 m, 22000 m, and 30000 m with a constant speed of Mach 5.

III. MATHEMATICAL MODEL

The Navier – Strokes equations which are formulations of mass, momentum, and energy conservation laws are solved.

A. *Conservation of mass (Continuity equation)*

The conservation of mass principle states that in the absence of mass sources and sinks, a region will conserve its mass on a local level. It is given as:

$$\frac{\partial \rho}{\partial t} + \nabla.[\rho\vec{v}] = 0 \qquad (1)$$

Where ρ is the density and v is the velocity of the fluid.

B. *Conservation of Momentum*

The conservation of momentum principle states that in the absence of any external force acting on a body, the body retains its total momentum (product of its mass and velocity). It is given as:

$$\rho\left[\frac{\partial \vec{v}}{\partial t} + (\vec{v}.\nabla)\,\vec{v}\right] = f \qquad (2)$$

Where f is the external force per unit volume acting on the material volume.

C. *Conservation of Energy*

It is governed by the first law of thermodynamics which states that energy can be neither created nor destroyed during a process; it can change from one form into another. It is given as:

$$\frac{\partial}{\partial t}(\rho e) + \nabla.[\rho\vec{v}e] = -\nabla.\left(\sum_j h_i J_j\right) + S_h \qquad (3)$$

IV. METHODOLOGY

The CAD models are created in Solidworks. The CFD analysis has the following steps:

A. Grid Generation

The grids for models are created using structured cartesian immersed – body mesh which consists of fluid cells, solid cells, and partial cells. The fluid cells and solid cells contain fluid and solid respectively. The partial cells contain both fluid and solid. Each cell is in the shape of a cuboid. The respective count of cells for different aircraft are listed in Table 1.

Model	Fluid cells	Solid cells	Partial cells	Total cells
Northrop B-2	197777	9230	6948	207007
Lockheed F-22	227896	842	826	228738
Hypersonic aircraft	465556	330825	208208	796381

Table 1:

B. Flow Conditions

The flow conditions including different boundary and initial conditions for different aircraft are shown in Table 2.

Parameters	Northrop B-2	Lockheed F-22	Hypersonic aircraft
Solver	Pressure based steady state	Pressure based steady state	Pressure based transient
Turbulence model	$k-\varepsilon$	$k-\varepsilon$	$k-\varepsilon$
Velocity (m/s)	281	669.444	Table from time
Angle of attack (degree)	0°	0°	Table from time
Initial pressure (Pa)	101325	101325	Table from time
Initial temperature(K)	293.20	293.20	Table from time

Table 2:

The conditions for hypersonic aircraft are time dependent. A transient state study for 5 seconds is used to analyze the hypersonic aircraft. The CFD analysis starts from 0^{th} second and ends at 5^{th} second. The dependency of various input parameters at their corresponding time step is tabulated in Table 3.

Time (s)	0	1	2	3	4	5
Altitude (m)	12000	12000	15000	18000	22000	30000
Velocity (m/s)	343	1715	1715	1715	1715	1715
Angle of attack (degree)	0	5	10	15	20	25
Initial pressure (Pa)	19330.4	19330.4	12044.6	7504.84	3999.79	1171.87
Initial temperature(K)	216.650	216.650	216.650	216.650	218.650	226.650

Table 3:

V. RESULTS AND DISCUSSIONS

The CFD analysis gives us the lift and drag coefficient along with lift and drag forces. The values of different parameters are plotted as graphs as follows:

A. Northrop B-2

This aircraft is a subsonic fighter jet. The vector plots for different iterations are given below.

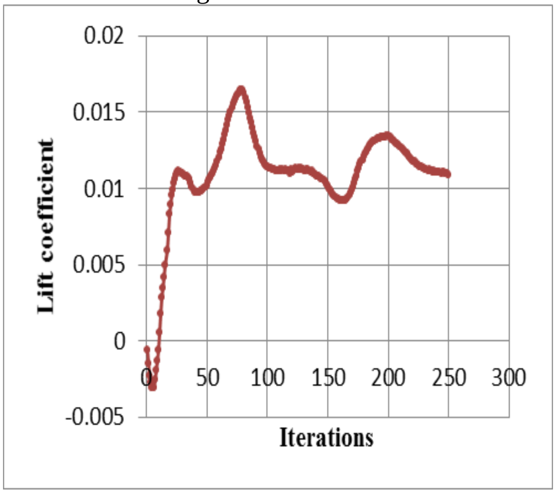

Fig. 2: Lift coefficient

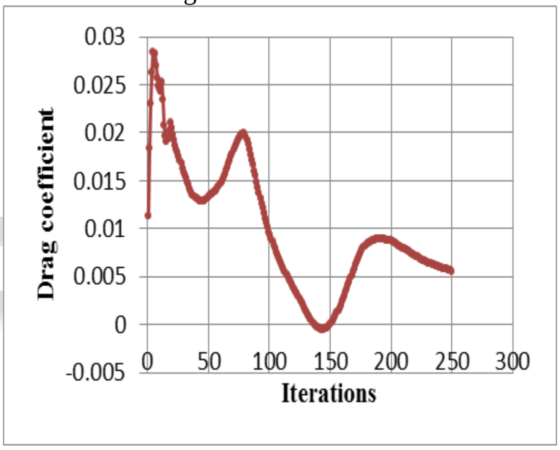

Fig. 3: Drag coefficient

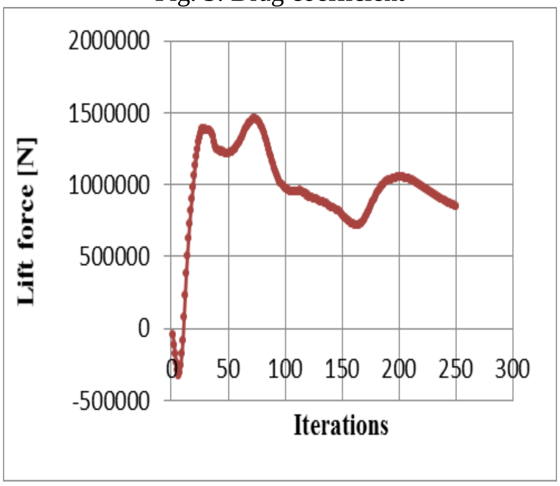

Fig. 4: Lift force

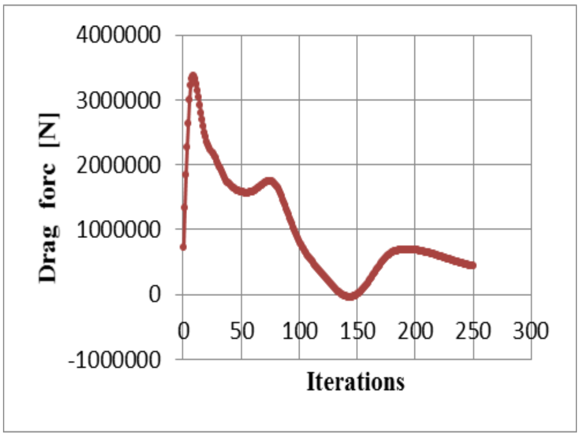

Fig. 5: Drag force

The average values of all iterations give the following results:

Name	Unit	Value
Lift coefficient	No units	0.0109101
Drag coefficient	No units	0.0055856
Lift Force	N	847707.743
Drag Force	N	434000.549

Table 4:

B. *Lockheed F-22*

F-22 is a supersonic aircraft that travels at speeds more than the speed of sound. The vector plots for different iterations are given below.

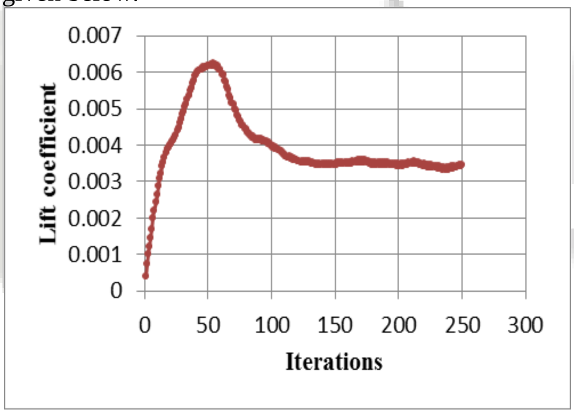

Fig. 6: Lift coefficient

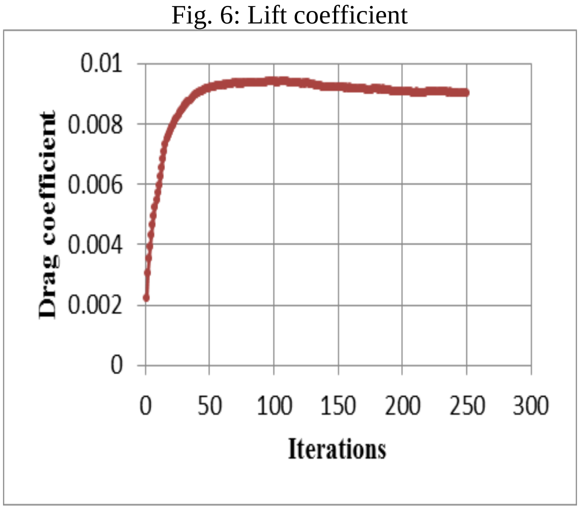

Fig. 7: Drag coefficient

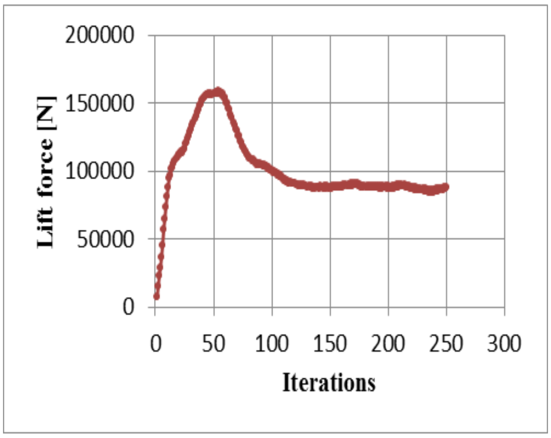

Fig. 8: Lift force

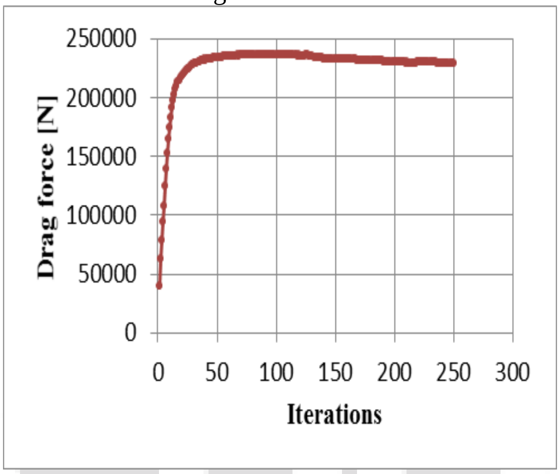

Fig. 9: Drag force

The average values of all iterations give the following results:

Name	Unit	Value
Lift coefficient	No units	0.0034572
Drag coefficient	No units	0.0090064
Lift Force	N	87776.237
Drag Force	N	228665.206

Table 5:

C. *Hypersonic aircraft*

Hypersonic aircraft is tested at Mach 5 starting from Mach 1 at 0^{th} second to Mach 5 at 5^{th} second. In addition to vector plots, streamlines, contours, and surface plots are obtained.

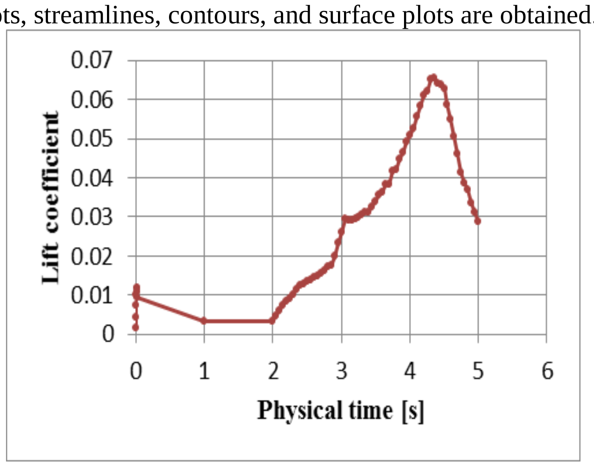

Fig. 10: Lift coefficient

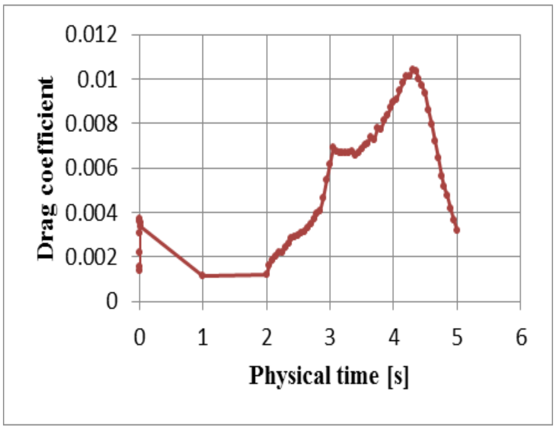

Fig. 11: Drag coefficient

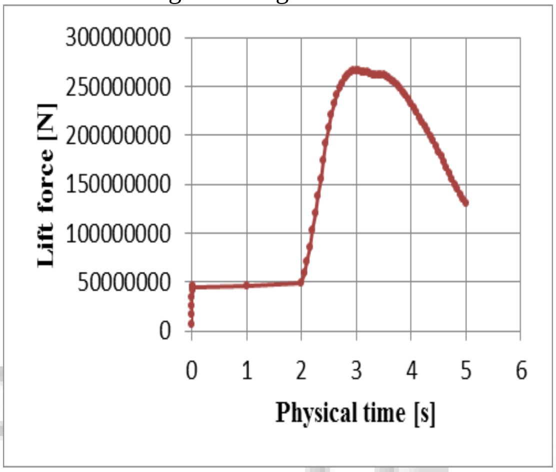

Fig. 12: Lift force

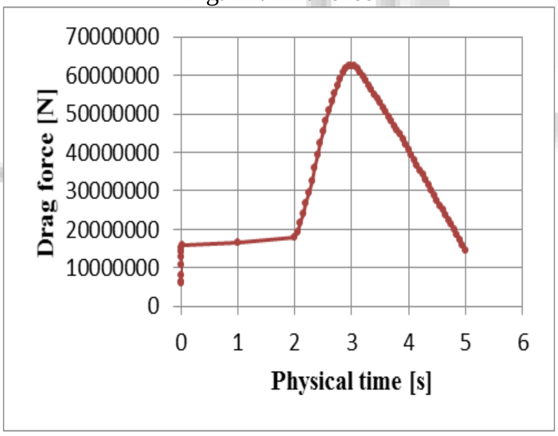

Fig. 13: Drag force

The average values of all iterations for different time steps are given below:

Name	Unit	Value
Lift coefficient	No units	0.0288081
Drag coefficient	No units	0.0031610
Lift Force	N	1.309e+008
Drag Force	N	1.437e+007

Table 6:

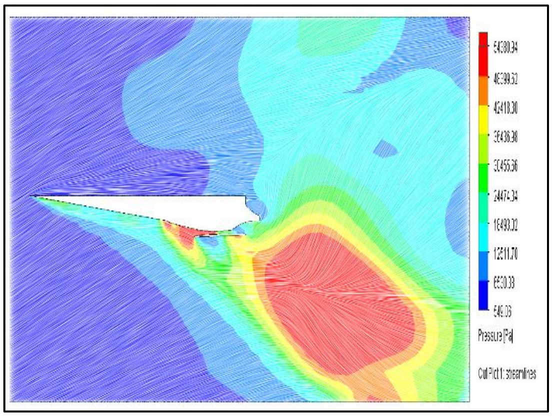

Fig. 14: Pressure contour

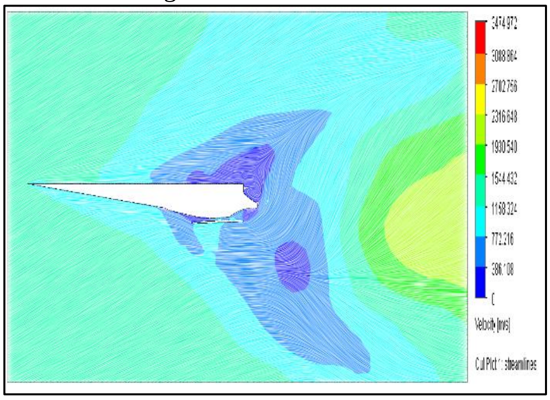

Fig. 15: Velocity contour

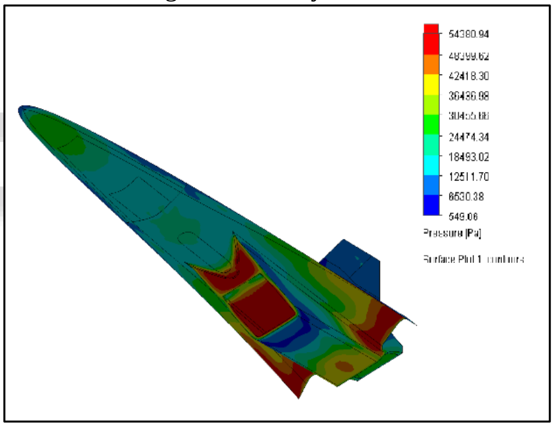

Fig. 16: Surface pressure distribution

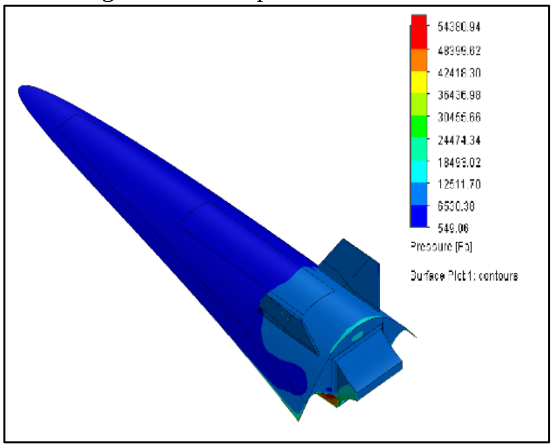

Fig. 17: Surface pressure distribution

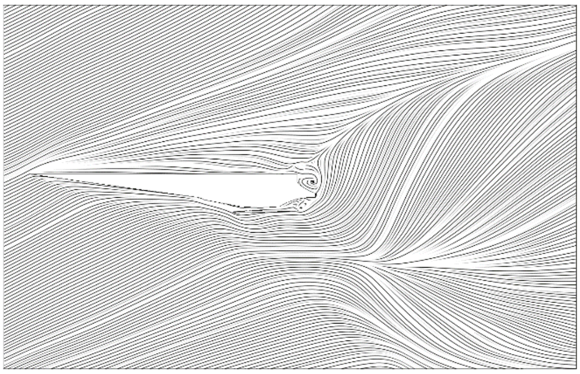

Fig. 18: Streamlines

D. Results interpretation

From the tables 4,5, and 6 it can be seen as the speed of aircraft increases from subsonic to hypersonic the aerodynamic drag of the aircraft increases rapidly. This aerodynamic drag increases the skin temperatures of the aircraft.

VI. CONCLUSION

The aerodynamic coefficients are calculated using Solidworks Flow Simulation solver using a real fluid model with air as working fluid. Based on the CFD study carried out on different aircraft at different speeds, the following conclusions are drawn

1) The aircraft skin friction increases rapidly when the speed increases from subsonic to hypersonic.
2) The surface temperatures of aircraft increase due to aerodynamic drag as the speed increases.
3) Shockwaves are created at supersonic and hypersonic speeds.

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