Numerical studies on Hypersonic Waveriders

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Abstract*— In the history books, aviation has always have been driven by the philosophy of "faster and higher", right from the start of the Wright brothers' sea level flights at 15.7 m/s in 1903, and progressing exponentially to the manned space flight mission of 1960s and 1970s. The efficient high speed aerospace vehicles need flow elements whether it is supersonic or hypersonic so that new aerodynamic design concepts can be developed. In supersonic and hypersonic vehicles, research is being conducted on about how the shock wave is formed at the leading edge of the lifting body. The challenging task is to control the bow shock wave formed at the leading edge and to find compatible surface for the aerospace vehicle. Waveriders are classical examples which can minimize this challenge by suitably increasing the lift to drag ratio. The waveriders are supersonic or hypersonic vehicles in which a shock wave is attached along its leading edge which will limit the leakage of the flow from lower to upper surface thereby increasing lift to drag ratio for any design configurations. A low L/D ratio will result in increase in requirement of fuel and thus a good L/D ratio is important. The design of a waverider is associated with aerodynamic efficiency, Mach number, lateral stability. Various numerical simulations are done at various positive as well as negative angle of attack to calculate the Mach number and also to observe the flow pattern.

***Keywords*—hypersonic, supersonic, waveriders, Mach number, angle of attack, shock wave.**

I. INTRODUCTION

History of aviation suggests that human beings has the curiosity to go "faster and higher" more effectively, right from the Wright brothers' sea level flights at 15.7 m/s in 1903, to the manned space flight mission of 1960s and 1970s [1]. One of the most complex and critical aspects was reentry into the atmosphere after completion of the lunar mission. The aerodynamic flight associated with very high-speed flight, such as encountered during reentry, is classified as hypersonic aerodynamics. Some other application on the horizon includes ramjet-powered hypersonic missiles. Concepts like hypersonic transport are being studied by NASA.

The maximum lift-to-drag ratio $\{(L/D)_{max}\}$ for a flight vehicle is a measure of its aerodynamic efficiency. For supersonic and hypersonic vehicles, as M_∞ increases, $(L/D)_{max}$ decreases drastically. There is a class of hypersonic vehicle shapes that generates higher value of L/D than other shapes. Such shapes are termed as waveriders.

A waverider is a supersonic or hypersonic vehicle that has an attached shock wave all along its leading edge. Because of this, the vehicle appears to be riding on top of its shock wave, hence the term "waverider".

The aerodynamic advantage of the waverider is that the high pressure behind the shock wave under the vehicle does not "leak" around the leading edge to the top surface. The flow field over the bottom surface is contained, and the high pressure is preserved, and therefore more lift is generated by the vehicle. In contrast to the generic vehicle, there is a flow between over the bottom and top surfaces. The pressure tends to leak around the leading edge, and the pressure level on the bottom surface is decreased, resulting in reduced lift. Due to this, generic vehicle must be flown at a larger angle of attack 'α', to produce the same lift as that of a waverider. Hence, waverider has significant advantage over the generic vehicles for sustained hypersonic cruising flight in the atmosphere.

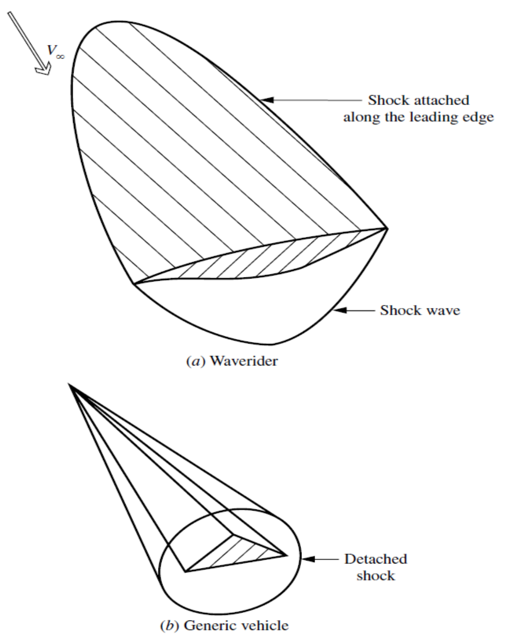


Fig 1: Schematic diagram of a waverider and a generic vehicle [5]

II. PHYSICAL ASPECTS OF HYPERSONIC FLOW

- The flow field that is being formed between the surface of the body and the shock wave is called shock layer.
- There are very thin shock layers which lie close to the surface of the body.
- The merging of shock layer with the boundary layer constitutes a fully viscous shock layer.

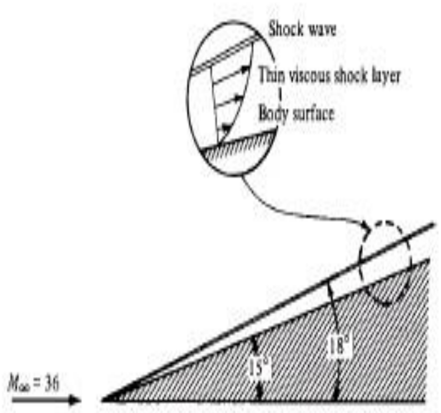


Fig 2: Shock waves characterized by thin shock layers [6]

III. TEMPERATURE EFFECTS OF HYPERSONIC FLOW

- Energy of the flow increases when Mach number is on the higher side of the spectrum.
- The ratio of kinetic energy to internal energy possessed by the gas depends on increase in $(M_\infty)^2$.
- The boundary layer is thick which deflects the inviscid, external flow by creating a strong curved shock wave which trails downstream from the trailing edge.
- Increase in the aerodynamic heating is due to high pressures at the leading edge.
- The shock layer formed behind the bow shock wave of a blunt is a region for high temperature. In this case thee flow velocity discontinuously decreases as it passes through the shock wave.

IV. NEWTONIAN THEORY

- Waveriders are based on the Newtonian theory.
- The Newtonian theory is used to describe the pressure distribution over the body surface.
- According to this theory, the flow will move tangentially to the surface consisting of large number of particles that will impact the surface of the body.
- The normal component of momentum of the flow particles will be lost, but the tangential component will still be preserved.
- The force exerted by the impact of the particle will be equal to the rate of change of the normal component of momentum.
- The coefficient of pressure at any point, is directly proportional to square of the sine of flow deflection angle, $C_p = 2\sin^2\theta$.
- Shock angle will be equal to the deflection angle at relatively large Mach numbers and moderately small deflection angles.

V. METHODLOGY

In this work, simulations are done on two configurations of hypersonic vehicles, i.e. Blunt (n3r6) waverider and Sharp (n3r0) waverider, are performed. We used ICEM CFD software for grid generation for both waveriders, and CFD++ software for simulations.

A. BLUNT WAVERIDER

1) *Grid Generation:* The geometry of blunt (n3r6) waverider was imported to ICEM CFD software. After importing the geometry of the waverider, domain around the waverider was created. A density box was also created in close vicinity around the geometry to better capture the shock waves. Surfaces were generated on the waverider and the domain. From these surfaces seven parts were created. Parts on the waverider are named as BOT, EDGE, TOP, representing bottom, edge, and top surfaces respectively. Parts on the domain are named as FF, SI, SO, SYMM, representing far field, supersonic inlet, supersonic outlet, and symmetry surfaces respectively. A body is created in between the domain and n3r6 waverider, namely, AIR, representing the medium in which the waverider is travelling. For grid independence study of blunt waverider, three blunt configurations were studied. This study gives the information of the variation of Cl/Cd w.r.t. number of elements in the mesh setup. Prism layers were created for all three configurations. Number of prism layers is 5x6 and prism ratio is 1.2. Prism layers are created on bottom, top and edge surfaces.

TABLE 1
MESH TYPES

S.No.	**Number of Elements (millions)**
1	0.86 (Coarse)
2	3.04 (Medium)
3	9.04 (Fine)

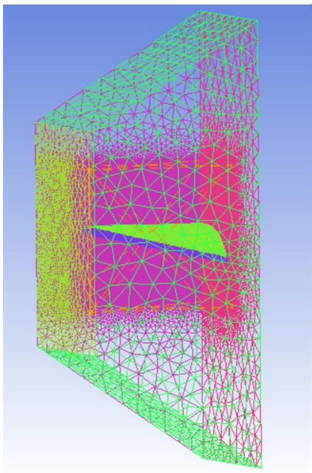
TABLE 2
MAXIMUM PART SIZE FOR EACH MESH TYPE

Mesh Type	**SI**	**SO**	**FF**	**SYMM**	**TOP**	**EDGE**	**BOT**	**DENS-ITY SIZE**

COA-RSE	50	50	50	50	3	3	3	6
MED-IUM	40	40	40	40	2	2	2	3.5
FINE	37	37	37	37	3	3	3	2

Mesh type is tetra/mixed in all three cases and mesh methods are robust (Octree), followed by Quick (Delaunay) method.

Figures below shows the meshing of all three mesh types



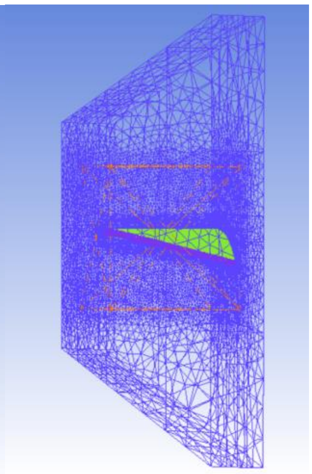


Fig 3: medium mesh type Fig 4: coarse mesh type

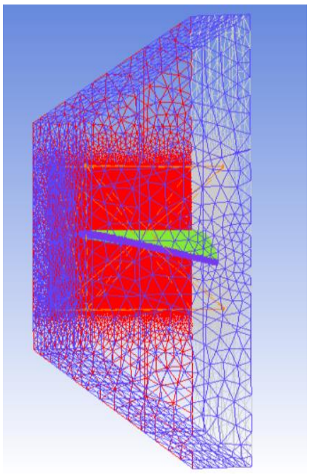


Fig 5: fine mesh type

2) *Simulations:*

The simulations were done on CFD++ software. The initial conditions that were used are:

- Mach number= 5.45
- Static Pressure= 2466.14 Pa
- Static temperature= 223.56 K
- Wall temperature= 300 K

For different angle of attacks, X and Y components of velocity were adjusted accordingly. The boundary conditions for the n3r6 are:

TOP, BOT, EDGE - Wall

SI- Supersonic Inflow

SO- Supersonic Outflow

SYMM- Symmetry

FF- Supersonic Inflow/Outflow

The number of iterations for the simulation= 3000.

Turbulence model used is 2-equation model (Realizable k-ε model).

B. SHARP WAVERIDER

1) *Grid Generation:* The sharp (n3r0) waverider consists of following parts: LE, LOWER, LOWER_1, UPPER, UPPER_1. The domain consists of following parts: FF, SI, SO, SYMM. A body is created in between the domain and n3r0 waverider, namely, AIR, representing the medium in which the waverider is travelling.

- Number of prism layers = 30
- Prism ratio = 1.2

TABLE 3

MAXIMUM PART SIZE

PART	MAXIMUM SIZE	HEIGHT RATIO
FF	56	1.3
LE	1.1	1.3
LOWER	2	1.3
LOWER_1	1.1	1.3
SI	56	1.3
SO	56	1.3
SYMM	56	1.3
UPPER	2	1.3
UPPER_1	0.995	1.3

Again, mesh type is tetra/mixed and mesh method is robust (Octree), followed by Quick (Delaunay) method. The number of elements in the grid is 3.9 million.

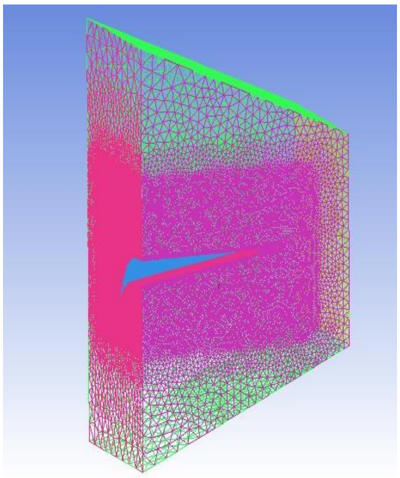


Fig 6: Grid for n3r0

2) *Simulations:* Similar initial conditions and turbulence model were used in the simulation process of n3r0 waverider. Boundary conditions for this simulation are:

LE, LOWER, LOWER_1, UPPER, UPPER_1 – Wall

SI- Supersonic Inflow

SO- Supersonic Outflow

SYMM- Symmetry

FF- Supersonic Inflow/Outflow

The number of iterations for the simulation= 3000.

VI. RESULTS AND DISCUSSIONS

Following plot gives descriptive information about grid independence study performed on blunt waverider.

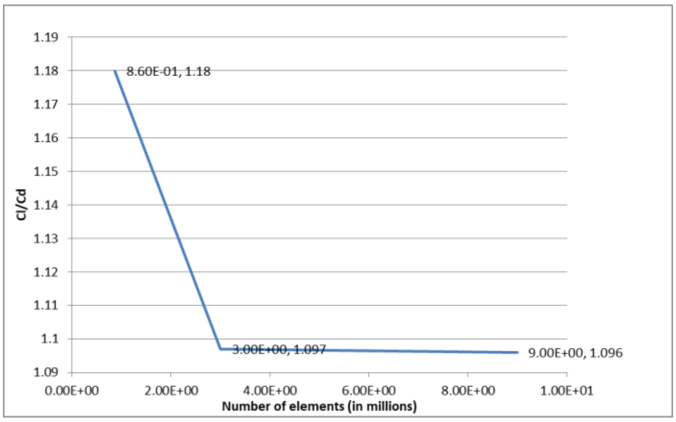


Fig 7: Grid Independence Study

According to this plot, the more fine the mesh, more computational time is required for the same simulation, because of large number of elements. Also, change in C_l/C_d is negligible as the number of elements in the grid increases. This is called Grid independence study. Mach number contours for the both n3r6 and n3r0 waveriders are shown below:

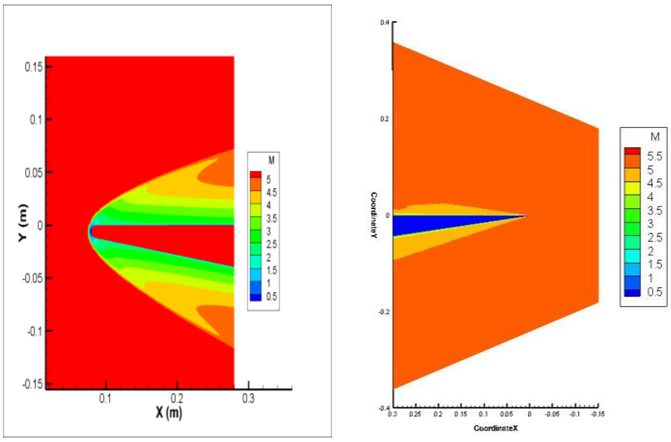


Fig 8: n3r6 and n3r0 at AOA -4º

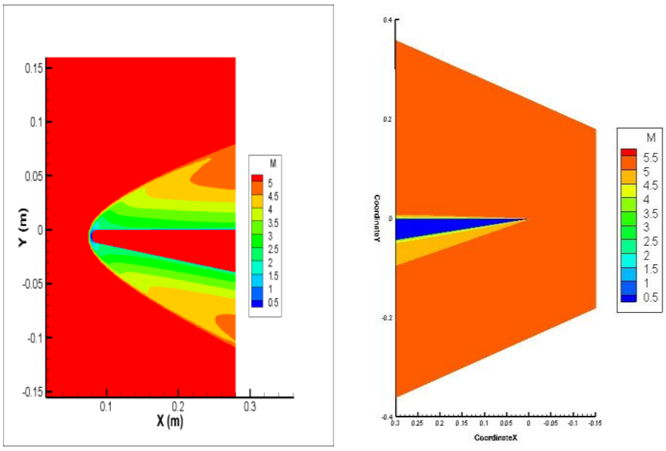


Fig 9: n3r6 and n3r0 at AOA -2º

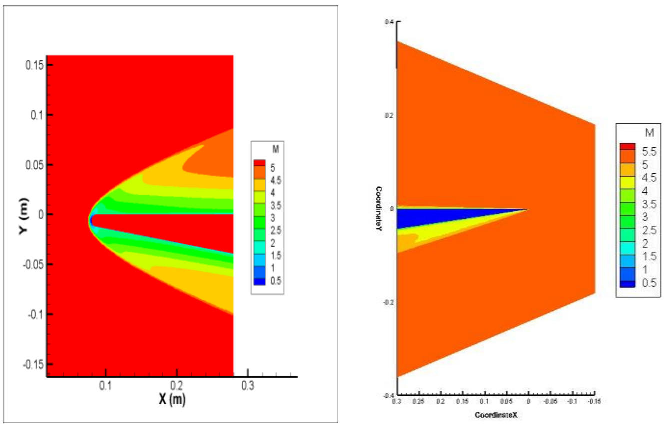


Fig 10: n3r6 and n3r0 at AOA 0º

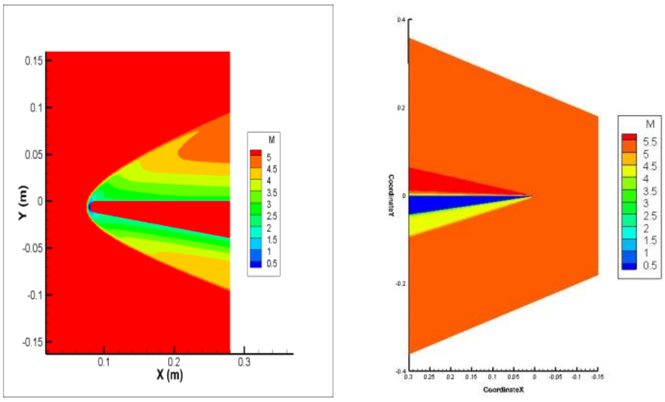


Fig 11: n3r6 and n3r0 at AOA 2º

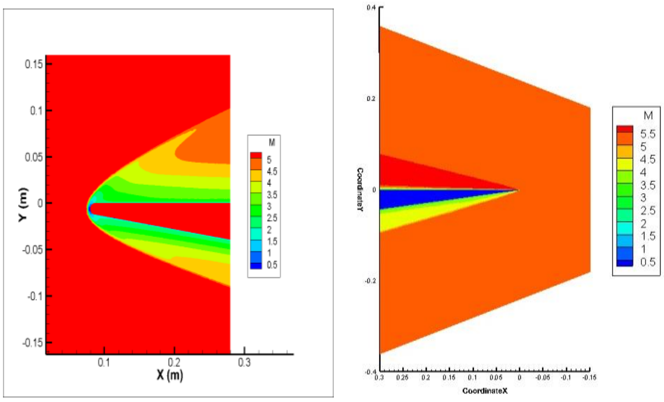


Fig 12: n3r6 and n3r0 at AOA 4º

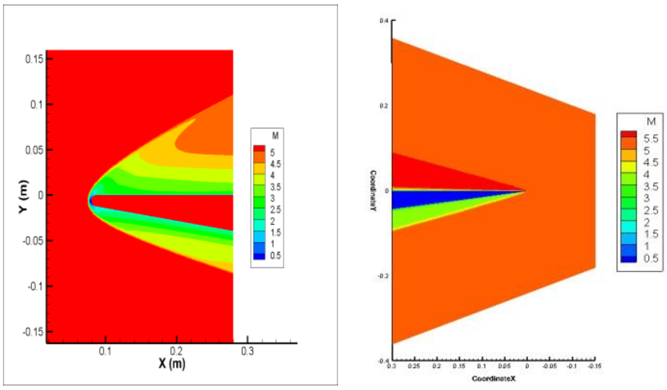


Fig 13: n3r6 and n3r0 at AOA 6º

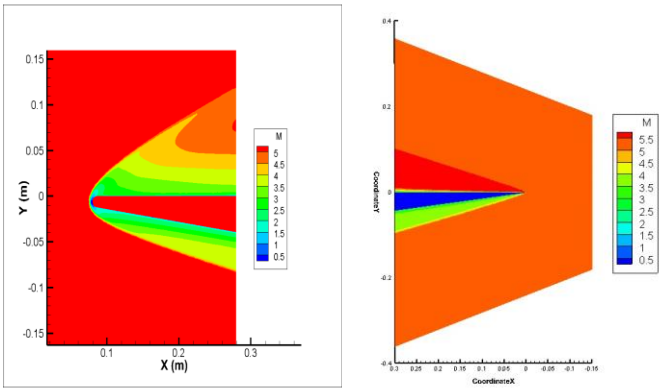


Fig 14: n3r6 and n3r0 at AOA 8º

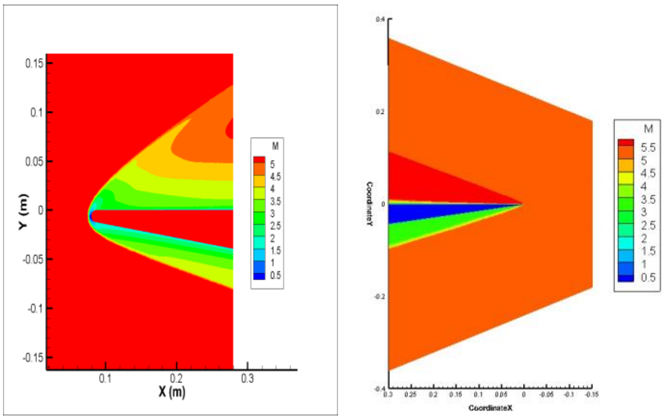


Fig 15: n3r6 and n3r0 at AOA 10º

The above contours suggest that as angle of attack increases, shockwaves moves towards the lower surface and moves away from the upper surface in both cases of the waverider. Thus, increasing the pressure on lower surface, producing more lift.

VII. CONCLUSION

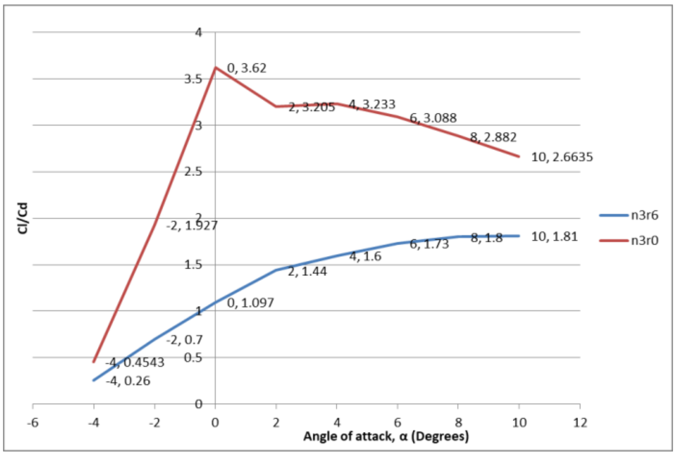


Fig 16: C_l/C_d VS α curve

By comparing two waveriders, from the above graph it is clear that even at zero degree angle of attack, sharp waverider provides much greater lift in contrast to the blunt waverider. Also for sharp waverider, both UPPER and UPPER_1 surfaces have high flow velocity, and with increase in angle of attack, C_l/C_d decreases, which is not the case with blunt waverider. Hence, if the application is straight level flight, then sharp edged waverider is preferable, as it provides much greater overall lift. If the application is a lot of manoeuvres with increased angle of attack, then blunt waverider is preferable. With the development of the aeronautical and astronautical technology, the design of the aircraft aims to the wider velocity range and larger space range [2][3], especially for the aerodynamic configuration design of the hypersonic vehicle.

VIII. APPLICATIONS

The waverider uses its cylindrical type geometry to launch satellites into low earth orbit. Waverider designs can be optimised for payload considerations for their usefulness in space missions. Waveriders can be used for military as a high altitude fighter and bombers with speeds above Mach number 4. They can be used as a missile concept which will have the ability to attack time critical targets compared to long range weapons and can also be used as reconnaissance aircrafts. Nowadays, there are some of the remarkable vehicles which are designed based on waverider configuration, such as X-51A [4]

IX. FUTURE SCOPE

Future of the waverider should be based on the control surface effectiveness along with aerodynamic data along all the various regimes of speed. Control surfaces may be designed in such a way such that longitudinal stability is ensured as well degradation of aerodynamic efficiency can be observed. Computational analysis must be implemented in order to compare the solutions with experimental data to provide information about flow field. For optimised design, blunt leading edge should be incorporated in order to control the aerodynamic heating at the leading edge. The performance of the waveriders can be improved by decreasing the detachment of the shock wave at a designated Mach number.

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