9th ANKARA INTERNATIONAL AEROSPACE CONFERENCE **AIAC-2017-079**
20-22 September 2017 - METU, Ankara TURKEY

CONCEPTUAL ANALYSIS AND OPTIMIZATION OF WAVERIDER BASED HYPERSONIC VEHICLE FORE-BODY INTEGRATED WITH RAMJET

Najam-us-Saqib[1] and Sajid Raza Chaudry[2]
Center for Excellence in Science and Technologies (CESAT)
Islamabad Pakistan

ABSTRACT

The research into design and development of hypersonic aircrafts and cruise vehicles is actively being pursued by leading nations of the world. The hypersonics ambitious program still has its technological gaps but fruits of active research can already be seen in the form of test flights of X-51demonstrator program. The leading candidate for hypersonic aircraft are waverider based vehicles. Waveriders get their name from the fact that this class of vehicles are designed to ride on the attached shock wave to its leading edges. The current research aims at developing a methodology for quick optimized configuration design analysis for fore body design of hypersonic waveriders in conceptual design phase.

INTRODUCTION

The advancement in the aerospace technologies has made it possible to endure the challenges of hypersonic flight for civilian applications. As a result, the next generation hypersonic vehicles have become prime area of research. One of the prime contenders of hypersonic aircraft design is the concept of waveriders. Waveriders are capable of producing high lift to drag ratios and provide favorable inlet conditions for air breathing ramjets and scramjets. Waveriders are developed from a known aerodynamic flow field and get their name due to the reason that they develop their lift force form the pressure difference between the windward and the leeward side. The origin of the waverider concept can be traced back to an experiment conducted by NASA research engineer, Dr. Alfred Eggers, in 1955. Dr. Eggers achieved a sixty-percent increase in L/D at Mach 5, over the technology of the time period, by creating a test vehicle with wing taper that matched the Mach 5 shock wave [Johnson,1994]. T. R. F. Nonweiler introduced the waverider concept of a three dimensional body optimized using a theoretical wedge flow field caret design [Nonweiler, 1959]. Later, Jones derived various waverider shapes from inviscid conical flow fields [Jones 1963]. The Caret design and the conical design lacked volumetric efficiency as well as limited geometric independence. Sobieczky, developed the osculating (Latin for“kissing”) cone solution which defines waveriders directly from a prescribed shockwave [Sobieczky,1990].

[1]Email: najam2u@yahoo.com
[2] Email:sajid039@hotmail.com

This inverse design method utilizes a desired leading edge shape and shockwave shape which can have a specified span wise variation of curvature. This results in better control of the integrated vehicle design. Thus osculating cones method has seen increased popularity as a means to obtain the generating flow field for waverider design. Current research utilizes osculating cones method to design and develop waverider fore body integrated with a ramjet inlet. An in-house code has been developed to provide optimized solutions for different design objective functions through global optimization tools.

FLOW FIELD GENERATION

Waverider lift generating surface is derived inversely from a known flow field calculated for the design mach number and cruise altitude. For a given cruise design mach number and altitude, conical flow field at zero angle of attack has been derived using Taylor Maccol equation [Anderson, 1982].

DEVELOPMENT OF WAVERIDER LIFT GENERATING SURFACE

Once a desired conical flow field is determined, streamlines are traced in order to develop a stream surface. This is done keeping in mind the basic definition of the streamlines which implies that flow through any two stream lines is always constant. Thus for the established conical flow field, streamlines lie along the planes of constant ø and each plane of constant ø is identical [Mary, 1992].

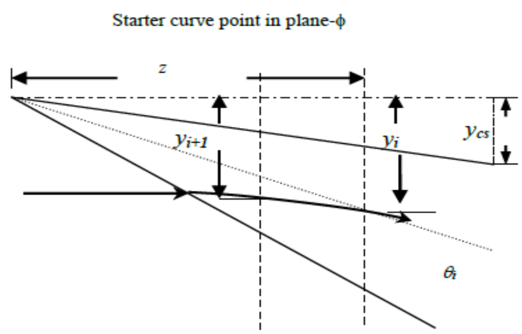

Figure 1: Pictorial depiction of the stream tube method

The upper and lower surfaces are treated independently in the case of waveriders. One of the most easy way to develop the upper surface is to trace the free stream streamlines back from the leading edge to define the upper surface , however if an expansion surface is traced using method of characteristics [Sobieczky,.1990] , it will aid in the increase of the lift force. Pictorial description of method is provided in Figure 1. A sample surface developed is shown in figure 2

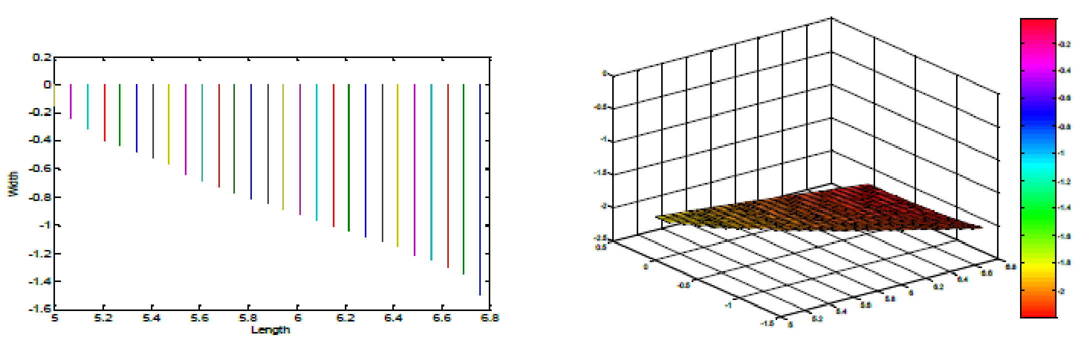

Figure 2: Lower surface generated for Mach 5 and cone angle of 15 degrees

WAVERIDER DEVELOPMENT THROUGH OSCULATING CONES METHOD

Osculating cones Method for development of the waverider lift generating surfaces is basically a strip flow method. It starts with a desired shock shape and then moves forward unlike conical waverider in which only one shock shape restricts the design. In this method conical slices of different radii are spliced together to form a complete shock layer. This method produces a virtual flow field generator with much less effort from a designer. This method provides a combination of a shock wave profile curve with either a lower or upper surface profile curve in the base plane, enable to derive uniquely full geometry of a waverider at On-design parameters. Figure 2 illustrates the osculating circle with radii for various osculating cones

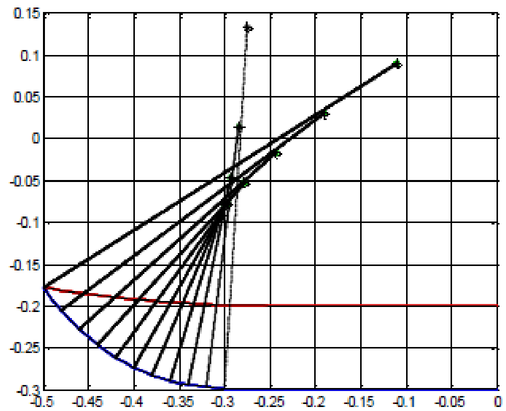

Figure 3: Radius points for osculating cones

VISCOUS LIFT AND DRAG CALCULATIONS

Viscous force calculation requires that flow along stream line is calculated. This has been done using reference conditions based on Eckerect‟s reference Enthalpy method [Eckert ,1956].

The transition criterion for the Laminar to turbulent boundary layer has been taken from Bowcutt and Anderson [Bowcutt, 1987]. The reference conditions are obtained using recovery temperature calculations and Sutherland‟s law.

Once the flow field properties along each stream line are known, in order to calculate forces acting on the vehicle surface, two adjacent streamlines are taken and then divided in to equal grid points. Next spline interpolation is used to calculate flow properties at each point. Once this is done, wetted area and forces along each triangular element is calculated. The whole lower surface is treated in the same way and the wetted area, pressure and shear force calculated accordingly through integration of the whole surface.

RAMJET MODULE INTEGRATION

For hypersonic flight vehicles in the regime of Mach 5, both ramjet and scram jet engines can be used. The reason is that efficient ramjet operations are around Mach 4 while an appreciable operational efficiency is achieved for scramjets above Mach 6 [Maurice, 2000].

Both the ramjet and scram jet engines work upon the Brayton cycle. The typical ramjet engine has following parts:

- Inlet Compression
- Isolator

- Combustion chamber
- Nozzle

In order to develop a numerical model for the system analysis of ramjet engine, Moerel and Halswijk [Moerel, 2005] work is worth mentioning. The combustion process is modeled by means of adding heat to the internal air mass flow. Generally, the pressure loss inside the combustion chamber is proportional to the mach number at the end of the intake [Wittenberg, 2000]. In the research literature, the ramjet combustion chamber temperatures in general vary from 2000 Kelvin to 2500 Kelvin [M. N. Bondaryuk, 1960] and the pressure in the ramjet engines range from 1.1 to 7 atmospheres or from 111.457 kPa to 709.275 kPa respectively. In view of the aforesaid, the temperature in combustion chamber has been assumed as 2000 Kelvin as an initial estimate for a conceptual design loop. The heat of reaction for the MCH Hydrocarbon fuel [Lobbia, 2004] has been considered as 43700 kJ/kg. The density of MCH has been taken as 770 kg/m^3. The ideal exit velocity can be calculated as

$$V_{exit} = V_{free}\sqrt{\frac{T_3}{T_{to}}}$$

Where V_{exit} is exit velocity of the nozzle, V_{free} is freestream velocity, T_3 is temperature at nozzle section entrance and T_{to} is the total stagnation temperature.

The thrust is obtained as

$$T_{ideal} = \dot{m}_o((1+f)V_{exit} - V_o)$$

Where T_{ideal} is the ideal thrust, m_o is mass flow rate at intake inlet, f is the air fuel ratio, V_o is free stream velocity. h_f is heating value of fuel per unit mass. T_3 is temperature of gases at exit of combustor chamber. T_o is free stream temperature at intake inlet. If for design purpose, the value of T_3 constrained at a known value, air fuel ratio value can be taken as following:

$$f_{ideal} = \frac{\frac{T_3}{T_o} - 1}{\frac{h_f}{c_{p_{air}} T_o} - \frac{T_3}{T_0}}$$

The thrust specific fuel consumption (TSFC) is given by following relationship, where T_{ideal} is the ideal thrust

$$TSFC = \frac{f}{\left(\frac{T_{ideal}}{\dot{m}}\right)}$$

RESULTS & DISCUSSION

Based upon the models discussed, a computational code has been written in Matlab to perform a conceptual design study for generation of a waverider fore body integrated with an isentropic inlet ramp using osculating cones method.

Two design objective functions have been developed for this research work. They address the two major issues of waveriders, the volumetric efficiency and the maximum lift to drag ratio at the same time keeping the isentropic inlet ramp size to optimal minimum to match the required engine cruise thrust. A relationship for sizing and optimizing of the isentropic ramp to size the inlet and thus estimate the engine performance as per desired requirement has been formulated in terms of thrust factor as following:-

$$thrust\_factor = (Thrust_{calc} - Drag_{calc}) / Thrust_{calc}$$

Thrust factor has been introduced to keep the thrust requirements as close as possible to the cruise requirements.

The maximum volumetric efficiency has been targeted in-order to develop a fore body with realistic and practical volume.

The objective function for maximum volumetric efficiency is as following

$$Fitness\_function = -Vol\_eff \times thrust\_factor$$

If a design is to be studied for maximum lift to drag ratio, an objective function can be written as following

$$Fitness\_function = -LbyD \times thrust\_factor$$

Consider a design problem defined as following

- Base width of the waverider configuration = 2 meters
- On design cruise altitude = 30,000 meters
- Design cruise Mach number = 5

Locating globally optimum designs is a difficult task. It requires sophisticated optimization algorithms and procedures. In typical optimization problems, there may be many locally optimal configurations. A downhill-proceeding algorithm, in which a monotonically decreasing value of objective function is iteratively created, may get stuck into local optima. In the view of aforesaid, global search algorithms like genetic algorithm (GA) can prove to be a better choice. GA is a generic probabilistic meta-heuristic and one of the most versatile techniques available for the global optimization for a given large search space. Therefore this research work incorporates GA as global optimization tool for optimizing the developed objective function.

Design variables have been given in Table 1. The engine box height has been kept at 0.4 meters as a constant, leaving width as a variable for optimizing the required the inlet size. The shock profile curve for osculating cones waverider generation has been taken as a tangent ogive curve while the geometry profiler curve has been selected as a power law curve for this research work. The results of the solution of the optimization problem are tabulated in Table 2.

Table 1 Design Space for Optimization of the problem

Design Variables	**Constraints**
Tangent Ogive shock curve radius ' R_{ogive}'	$0.07 \le R_{ogive} \le 0.3$
Profiler Power law curve exponent 'x'	$0.05 \le x \le 0.7$
Width of engine inlet 'E_{ramp}'	$0.05 \le E_{ramp} \le 0.38$

Initial guess plays very important role in GA to reach the global optima. Initial population has been generated through Latin Hypercube Sampling (LHS). The GA has been run for 20 generations with cross over fraction set as 0.8. The graphical results of the best and mean values of objective function for every generation have been plotted. Figure 3 shows results of 20 generations for fitness function for max L/D and Figure 4 shows results for fitness function for maximum volumetric efficiency. The geometric profiles developed from optimized design variables are plotted in Figure 6 and Figure 7 respectively.

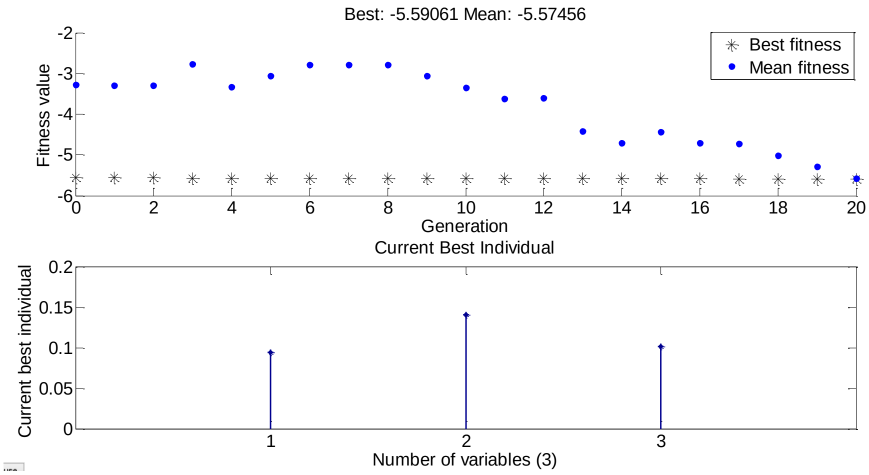

Figure 4: Max L by D results of GA plotted for 20 generations

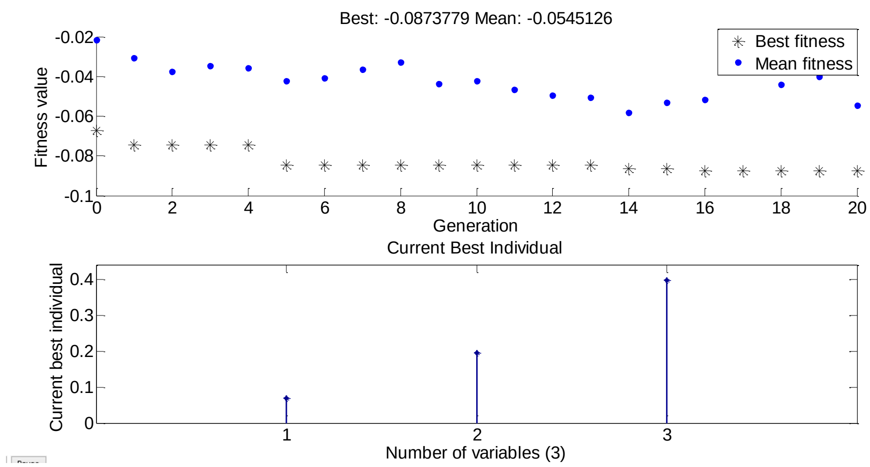

Figure 5: Max Volumetric Efficiency results of GA plotted for 20 generations

Table 2 Optimized Solution Results

Fitness Function	**L/D**	**Volumetric Efficiency**	**Optimized Design Variables (Best Individual)**		
			x	**R_{ogive}**	**E_{ramp}**
$LbyD \times thrust\_factor$	9.59	0.0746	0.0943	0.1407	0.1013
$Vol\_eff \times thrust\_factor$	8.99	0.1237	0.1376	0.1949	0.39681

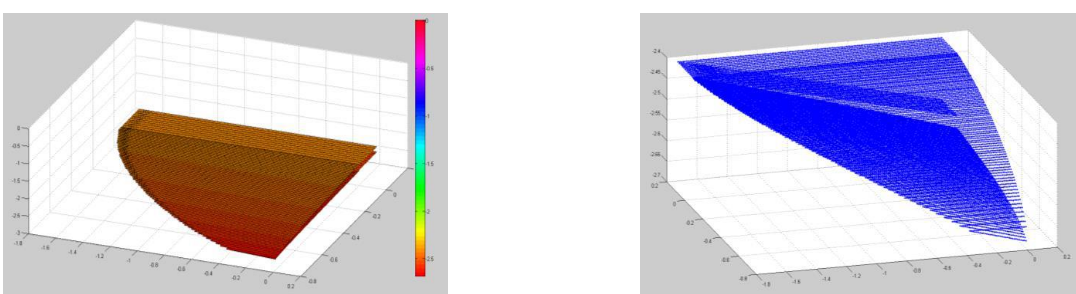

Figure 6: Perspective view of optimized waverider configuration for Maximum L By D

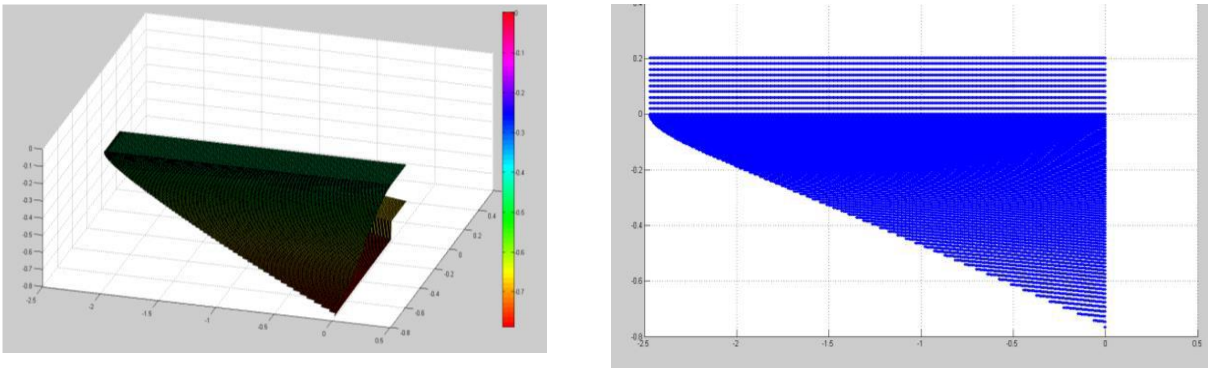

Figure 7: Perspective view of optimized waverider configuration for Maximum Volumetric Efficiency

CONCLUSION

The conceptual design methodology developed in this research work provides a good initial design simulation tool for optimizing hypersonic waverider based vehicles fore-body using osculating cones method for integration with ramjet engine. The optimized geometrical configuration developed can be further analyzed for high fidelity design analysis. In future scramjet conceptual design model can also be integrated in the developed design methodology

REFERENCES

Anderson John ,Jr(1982), *Modern compressible flow: with historical perspective*, McGraw hill New York 1982

Bowcutt, K. G., Anderson, J. D., Capriotti, D (1987). *Viscous Optimized Hypersonic Waveriders,* Proceedings of the 25th AIAA Aerospace Sciences Meeting, Reno, Nevada, January 1987. AIAA-87-0272

Eckert E R G (1956). *Engineering relations for Heat transfer and Friction in high –velocity Laminar and Turbulent Boundary layer Flow over Surfaces with Constant pressure and temperature*, Transaction of ASME, 1956, 78(6): 1273

J.L.P.A Moerel and W.M.C. Halswijk (2005), *System Analysis of High Speed Long Range Weapon Systems*, AIAA Atmospheric Flight Mechanics Conference and Exhibit San Fransisco California 15-18 August, 2005. AIAA-2005-5819

Johnson L. M.(1994), *Hydrodynamic Flow field Visualization Studies Of a Mach 6 Waverider*, M.Sc. Thesis Naval Postgraduate School, Monterey, California

Jones J. G. A (1963) *Method for Designing Lifting Configurations for High Supersonic Speeds Using the Flow Fields of Non-Lifting Cones*. Royal Aircraft Establishment, Report 2674.

Lobbia M A (2004). *A Frame Work For The Design And Optimization Of Waverider – Derived Hypersonic Transport Configurations*, PhD. Dissertation, University of Tokyo.

Mary Kae Lockwood O‟Neil (1992) *Optimized Scramjet Engine Integration on a Waverider Airframe,* Phd Dissertation University of Marryland college park

Maurice L, Edwards T (2000). *Liquid Hydrocarbon Fuels for Hypersonic propulsion*, AIAA progress in Astronautics and Aeronautics: Scramjet Propulsion, 2000, 189(11):P 697-755

M. N. Bondaryuk, S. M. II'yashenko (1960) *Ramjet Engines Part 1 of 2 parts* AD 607169 Report

Nonweiler T. R. F (1959), *Aerodynamic Problems of Manned Space Vehicles,* Journal of The Royal Aeronautical Society, 1959 63: P521-528.

Sobieczky, H., Dougherty, F., Jones, K.D.(1990*) Hypersonic Waverider Design From Given Shock Waves*. 1st International Hypersonic Waverider, Symposium, University Of Maryland, College Park, MD, Oct. 1990.

Wittenberg H (2000) *. Some Fundamentals on the Performance of Ramjets with Subsonic and Supersonic Combustion*, TNO-PML/2000