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A System of Computer Programs to Calculate Aerodynamic Characteristics for Missiles, Reentry Vehicles, and Spacecraft at Angles of Attack

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A SYSTEM OF COMPUTER PROGRAMS TO CALCULATE AERODYNAMIC CHARACTERISTICS FOR MISSILES, REENTRY VEHICLES AND SPACECRAFT AT ANGLES OF ATTACK

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Introduction

At the Fifth Space Congress, a method was presented for predicting the inviscid gas properties surrounding blunt nosed aerospace vehicles in supersonic or hypersonic flight, at zero angle of attack (Reference 1). Two computer programs used in combination were utilized. At that time it was indicated (References 1 and 2) that this capability was to be extended, using a new unique system of eleven different computer programs, in order to provide for the calculation of gaseous properties and aerodynamic characteristics for vehicles flying at angles of attack. At angles of attack, the problem of predicting the gas properties and aerodynamic characteristics is an order of magnitude more difficult due to the fact that the flow field is three-dimensional. That is, the flow properties vary in all three directions: as a function of body axial station, location around the body (at a given station), and distance away from the body. The newer set of programs also provides the capability of handling vehicles with sharp as well as blunt noses, and includes the capability of predicting the viscous flow boundary layer properties on the vehicle surface. Most of the programs were originally developed under U.S. Air Force and Army Contracts by General Applied Science Laboratories. The programs were converted to operate on the Control Data Model CDC 6400 digital computer used at Martin Marietta Corporation's Orlando Division. Over the past year, many modifications have been made to the system of computer programs to increase the efficiency of utilization (by simplifying the inputs required, etc.), reduce the computer run time (cost of operation), and to increase its capability (calculate aerodynamic characteristics etc.).

At present, these programs can be used in combination to generate three-dimensional, inviscid and viscous, perfect and real gas, flow fields for blunt or sharp nosed vehicles at angle of attack.

These programs are necessary for vehicle preliminary design and analysis. They are used:

(a) to determine the properties on the vehicles surface which are required to:

- (i) calculate aerodynamic coefficients for determining vehicle performance and flight stability,
- (ii) calculate vehicle loads for doing stress analyses and determining aeroelastic effects,
- (iii) correlate data obtained in wind tunnels and flight test,
- (iv) obtain data for heat transfer analyses.

(b) to determine the properties in the vehicle's shock layer which are required to:

- (i) determine airbreathing propulsion system inlet locations,
- (ii) conduct rain and ablated particle impact erosion studies,
- (iii) calculate the aerothermodynamic and electromagnetic properties in the plasma sheath for predicting communications problems,
- (iv) conducting vehicle control studies by providing flow fields in the neighborhood of control surfaces and reaction control system jets (using jet interaction and external burning control techniques).

This unique capability, consisting of the computer programs to be described in this paper, has been used to generate information for the following U.S. Air Force, Army, and Navy Missile Projects:

SAM-D:	Surface to Air Defense Missile
LVRJ:	Low Volume Ramjet Missile
TARSAM:	Thrust Augmented Rocket Surface to Air Missile
AGMX-3:	Air to Ground Missile Experimental
SPRINT:	Solid Propellant Rocket Interceptor Antiballistic-Missile Missile
SHORAD:	Short Range Air Defense Missile
AFAADS:	Advanced Forward Anti-Aircraft Defense System
BDM:	Bomber Defense Missile

List of the Computer Programs in the System

The eleven programs are listed below:

FO-091	Cone - Real
FO-092	Cone - Perfect
FO-093	BLNT-2D - Real
FO-094	BLNT-2D - Perfect
FO-095	ROTAX
FO-096	3DMOC - Sharp
FO-097	3DMOC - Blunt
FO-098	BONLAY
FO-099	AERO
FO-100	STRMLN
FO-101	PLOT

Functions of the Computer Programs

The functions of the programs listed above will now be described briefly:

FO-091 - This program determines the real gas solution for the flow properties surrounding a conically shaped missile at angle of attack. This program will also generate a tape that can be used as input (starting conditions) for program FO-096 described below.

FO-092 - This program determines the ideal gas solution for the properties surrounding a conically shaped missile at angle of attack.

This program will also generate a tape that can be used as input (starting conditions) for program FO-096 described below.

FO-093 - This program determines the real gas solution for the properties surrounding the spherical cap of a blunt nosed missile at angle of attack, which is used as input to program FO-095 described below.

FO-094 - This program determines the ideal gas solution for the properties on the spherical cap of a blunt nose missile at angle of attack, which is used as input to program FO-095 described below.

FO-095 - This program rotates the coordinate system, from a wind axis system to a body axis system, which is essential for obtaining a three-dimensional flow field. This program uses as input the output tapes generated by programs FO-093 or FO-094. The program then generates an input tape for program FO-097 described below.

FO-096 - This program calculates the real or ideal gas three-dimensional inviscid flow field around sharp nosed missiles at angle of attack. The program uses the output tapes generated by computer programs FO-091 or FO-092 as input.

FO-097 - This program calculates the real or ideal gas three-dimensional inviscid flow field around blunt nosed missiles at angle of attack. The program uses the output tapes generated by computer program FO-095 as input. The program then generates input for computer programs FO-098 through FO-101 described below.

FO-098 - This program calculates the real gas three dimensional boundary layer properties around blunt nosed missiles at angle of attack. The program uses the output tape generated by computer program FO-097 as input, which provides the inviscid boundary layer edge properties which are to be matched using the viscous flow boundary layer solution in this program.

FO-099 - This program calculates the aerodynamic coefficients for both sharp and blunt nosed missiles at angle of attack, using the output tapes from programs 3DMOC FO-096 or FO-097 as input.

FO-100 - This program determines the location of body and field streamlines in the inviscid flow field using the output tapes from programs 3DMOC FO-096 or FO-097 as input.

FO-101 - This program will, when completed, plot the desired results from all of the above programs (with the exception of FO-093, FO-094, and FO-095) using the corresponding output tape as input.

Thus, in order to generate perfect gas flow fields around a blunt nosed vehicle at angle of attack, computer programs BLNT2D-PERFECT, ROTAX, 3DMOC-BLUNT, and BONLAY (programs FO-094, FO-095, FO-097, FO-098, respectively) are used. Computer programs CONE-PERFECT and 3DMOC-SHARP (programs FO-092 and FO-096) are used to calculate the flow field around a sharp nosed vehicle at angle of attack. The aerodynamic coefficients are then calculated from these flow fields using program AERO (program FO-099). All of the significant results obtained will then be plotted using program PLOT (program FO-101).

A flow chart describing how the programs are used in combination is shown in Figure 1.

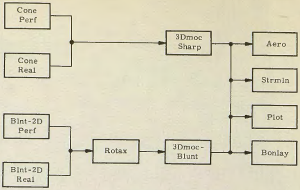

Figure 1 - System of Programs

General Description of Capability and Usage of the System of Programs

A system of eleven computer programs (FO-091 through FO-101) are used in combination to generate three-dimensional inviscid and viscid, perfect or real gas flow fields and, aerodynamic characteristics for vehicles at angle of attack. Sharp nosed and spherically capped blunt nosed vehicle configurations of arbitrary shape (without flares) can presently be handled.

To determine the flow properties around, and the aerodynamic characteristics of, a blunt nosed spherically capped vehicle at angle of attack, flight conditions are input to the BLUNT-2D computer program. The program then determines the solution for the flow field around the spherical nose in wind coordinates. Subroutine BLUNT calculates the aerothermodynamic parameters in the subsonic and transonic flow regimes, using a direct time-dependent modified Lax-Wendroff technique. Subroutine 2D calculates the supersonic portion of the flow field around the spherical cap that is still axisymmetric regardless of the angle of attack, using an axisymmetric method of characteristics technique. This flow field is stored on tape and provided as input to program ROTAX which accounts for the angle of attack and transforms the flow field from a wind reference frame coordinate system to a body reference frame coordinate system. It also determines at what body axis station the flow becomes asymmetric due to the angle of attack. ROTAX then provides a starting line at this axial station in the body axis coordinate system for 3DMOC, the three-dimensional method of characteristics program, on tape, which is used as input to 3DMOC. This program computes the complete asymmetric portion of the inviscid flow field around the entire vehicle, prints it out, and also stores it on tape. This tape is provided as input to programs BONLAY, AEROCO, STRMLN, and PLOT. Bonlay computes all of the boundary layer characteristics near and on the vehicles' surface, and also traces streamlines on the vehicles' surface. The output parameters from the three-dimensional method of characteristics program (computer program FO-097) pertinent to the three dimensional boundary layer calculation (computer program FO-098) are recorded on tape during the three-dimensional inviscid flow field computation. This tape then serves as input to the three-dimensional boundary layer program and provides the necessary inviscid information for the calculation of the three-dimensional boundary layer.

For a sharp nosed vehicle at angle of attack program CONE provides, on tape, the body axis reference frame starting line to the 3DMOC program analogous to the way program ROTAX supplies this information to 3DMOC for a blunt nosed vehicle.

The complete inviscid flow field around the entire vehicle is printed out and stored on tape for use as input to programs AEROCO, STRMLN and PLOT. At present there is no boundary layer analysis similar to BONLAY for a sharp nosed vehicle.

Program STRMLN, using the 3DMOC output tape as input, traces both body and field streamlines in the inviscid flow field and calculates pressures and velocities along these streamlines. This program is presently being modified.

Program PLOT is being developed as a general curve plotting program which will automatically plot the significant results of programs CONE, 3DMOC, BONLAY, AERO and STRMLN using their respective output tapes as input.

Analyses Utilized in the Computer Programs

A short description of the methods, analyses, and techniques utilized in these programs will now be given.

Program CONE - Cone Program for Cones or Sharp Nosed Bodies at Angle of Attack (FO-091 and FO-092)

The cone at angle of attack program uses a Lax-Wendroff finite difference technique for the solution of the interior supersonic flow field. The elliptic equations for the supersonic conical flow around a sharp cone are transformed to hyperbolic equations by considering the flow to be dependent upon the spherical space geometry coordinate r . Allowing r to tend to very large values, a conical state will be reached asymptotically and conical flow established independent of r . The shock and body points are obtained using a method similar to the one used in the three-dimensional method of characteristics program (FO-096 and FO-097). Perfect gas or real gas (equilibrium air) solutions can be obtained.

Thus, the solution of the cone at angle of attack is obtained from the solution of the steady state equations of motion in spherical coordinates. Since the flow is supersonic, the equations are hyperbolic. The final solution is independent of the radical coordinate. (The flow must be conical.) More details of the analysis can be found in Reference 3.

Program BLNT2D - Blunt Body Program for Blunt Nosed Bodies at Angle of Attack (FO-093 and FO-094)

The new blunt body program uses the direct method with a Lax-Wendroff finite difference technique for the solution of the interior subsonic flow field. The elleptic equations describing the subsonic flow field are transformed to hyperbolic form by introducing time dependence into the equations. The steady state solutions to the time dependent equations are then obtained giving the desired interior subsonic blunt body flow field. The conditions behind the shock and on the body are obtained using the techniques employed in the three-dimensional method of characteristics program. This program has perfect and real gas (equilibrium air) capability.

Thus, the blunt body solution uses a time dependent technique with the Eulerian equations of motion in their complete unsteady form. This makes the equations hyperbolic and the problem is reduced to a Cauchy initial value problem. After an initial guess for properties around the body, the solution at each subsequent time step is obtained by a finite difference method at the points between the body and the shock. At the body and shock, the points are handled using a method similar to the one used in the three-dimensional method of characteristic program. More details of the analysis are presented in Reference 4.

An axisymmetric method of characteristics program has been combined with the blunt body program in order to provide the remaining portion of the axisymmetric flow field around the spherical cap of the spherically capped blunt body.

Program ROTAX - Rotation of Coordinate Axes Program (FO-095)

This program simply transforms the coordinate axes from a wind axis system to a body axis system. Although this program is by far the smallest of the programs in the system, it is a significant step in the calculation procedure. It eliminates the necessity of calculating the flow field in the wind axis coordinate system where one gets a very bad distribution of field points. The mesh on the windward side is too fine and the mesh on the leeward side of the body is too coarse. The mesh size of the calculation intervals for the field points obtained using the rotated body coordinate axes system is necessary for the calculation of a truly useful three-dimensional flow field calculation.

This rotation of axes program is the key to success for the system of programs used and described herein. The difficulty of making the calculation in the wind coordinate axis system is the biggest drawback of the flow field computer programs under development elsewhere.

Program 3DMOC - Three Dimensional Method of Characteristics Program for Blunt or Sharp Nosed Bodies at Angle of Attack (FO-096 and FO-097)

As the name implies, this program uses a three-dimensional method of characteristics analysis to compute the entire inviscid flow field. The specific details of the analysis can be found in Reference 5.

Program BONLAY - Three Dimensional Boundary Layer Program for Blunt Nosed Bodies at Angle of Attack (FO-098)

The boundary layer edge properties are obtained from the flow properties of the inviscid flow field at a distance from the missile surface equal to the local boundary layer thickness. This takes into account the effect of mass entrainment and swallowing in the three-dimensional flow field. Specifically, the velocity vector at the local boundary layer edge is followed to the next station where a new thickness, edge condition, and velocity vector are found. Thus, the boundary layer around the body is computed along a pseudo-streamline (not a line of constant entropy). This allows more mass to participate in the viscous phenomenon as the boundary layer grows, and thereby accounts for the effect of swallowing. The consideration of mass swallowing is important in three-dimensional flows for bodies at angle of attack because of the strong entropy and pressure gradients on the windward side of the body, and the non-uniform entropy distribution around the body.

Thus, the analysis considers the effect of mass entrainment by determining the boundary layer thickness from the local inviscid flow properties in the three-dimensional flow field. The method utilizes the local entropy and pressure existing in the inviscid flow field at a distance from the body surface equal to the boundary layer thickness. The boundary layer equations are solved in an interative manner so that the inviscid edge properties match the boundary layer thickness computed from these edge properties.

The boundary layer program has three options:

1) Fully laminar flow
2) Fully turbulent flow
3) Transitional flow.

The boundary layer analyses are based upon the work of R. Vaglio-Laurin in References 6 & 7.

If the type of boundary layer that exists on the vehicle has not been determined a-priori, (i.e. laminar, turbulent, or both), the transition criteria option can be employed. The parameter used to determine the location of the transition point is the Reynolds number based on the momentum thickness. The laminar analysis option of the program is utilized until the transition Reynolds number is attained. At this point, the turbulent option is automatically employed.

Programs AERO, STRMLN and PLOT do not contain sophisticated analyses, as they use numerical integration and interpolation schemes and techniques.

Inputs Required For All Programs

Program CONE

The input required for the calculation of perfect or real gas: (1) inviscid flow fields around conical shaped vehicles at angles of attack, and (2) initial conditions (starting line) for the Three-Dimensional Method of Characteristics Program for axisymmetric sharp-nosed vehicles of arbitrary configuration at angles of attack, are as follows:

- flight conditions (the free stream static pressure, static enthalpy, ratio of specific heats and, the vehicles velocity),
- gas model (real or perfect gas),
- nose-tip conical half-angle,
- angle of attack,
- the calculational mesh size desired (in the r and θ directions), which also determines the locations at which data is obtained, and
- an additional quantity representing an approximation to the shock wave angle (the initial guess should be the value of the shock angle for the cone at zero angle of attack).

Program BLUNT-2D

The input required for the calculation of perfect or real gas (1) inviscid flow fields around spheres, and (2) initial conditions for the Three-Dimensional Method of Characteristics Program for axisymmetric spherically capped blunt-nosed vehicles of arbitrary configuration at angles of attack, are as follows:

- flight conditions (the free stream static pressure, static enthalpy, ratio of specific heats and, the vehicles velocity),
- gas model (real or perfect gas),
- the calculational mesh size desired (in x and y directions) and,
- an additional quantity X_t which is the terminal location of the two-dimensional (axisymmetric) method of characteristics calculation.

When this program is used for item (2) above, the maximum value of X_t should be

$$X_t = \cos (90^\circ - \alpha + \theta_c)$$

where α = maximum angle of attack of interest,
θ_c = the effective nose cone half-angle of the vehicle.

Program ROTAX

The input required for the calculation of the initial conditions (starting line) in the body axis reference frame as required by the Three Dimensional Method of Characteristics Program are as follows:

- flight conditions (the free stream static pressure and density, and the free stream ratio of specific heats and, the vehicle velocity),
- gas model (real or perfect gas),
- vehicles effective nose conical half-angle (i.e., the cone half-angle of the conical section attached to the spherical nose),
- angle of attack,
- the calculational mesh size desired (in the r and θ directions), which also determines at which location data is obtained,
- option for that portion of the flow field desired in the θ direction (e.g., for the windward side of the vehicle only, $\theta = 0°$ to $\theta = 90°$).

Program 3DMOC

The Three Dimensional Method of Characteristics Program, 3DMOC, calculates the complete perfect or real gas inviscid flow field, for axisymmetric sharp or blunt nosed vehicles of arbitrary shape, at angles of attack. The inputs required for this program are:

- control words for digital computer system operation (card input vs. tape input etc.),
- gas model (real or perfect gas),
- the calculational mesh size desired (in the r and θ directions),
- the vehicle geometry (body shape in x and y coordinates),
- parameters for the calculation of aerodynamic coefficients, including:
- the nose radius (zero for a sharp nose),
- the angle of attack, and
- a reference dimension and area.
- indicators for the various options available including:
- the nose tip option (sharp or blunt nose),
- the option to calculate and obtain aerodynamic coefficients, and
- the option to automatically plot the significant results parametrically with either the digital computer (on the computer printout sheets) or Calcomp plotters (on graph paper).
- the option of printing data at desired frequencies in all three directions (r, θ and z).

Program BONLAY

The input required for the calculation of real gas (excluding perfect gas) boundary layer characteristics for spherically capped axisymmetric blunt nosed (excluding sharp nosed) vehicles of arbitrary shape, at angles of attack are:

- flight conditions (the free stream, pressure, density and velocity),
- angle of attack,
- vehicle geometry (cone frustrum approximation and nose radius),
- option indicator for the type of boundary layer

to be considered (laminar, turbulent, or transitional),
- the number of, and the initial angular location of, the body streamlines to be traced around the missile surface (maximum of 10),
- longitudinal vehicle surface (wall) temperature distribution and,
- an output frint frequency indicator option (to obtain information at desired locations only).

Program AEROCO

The input required for the calculation of aerodynamic coefficients for both sharp and blunt nosed vehicles are:
- body length
- reference area
- reference diameter
- reference for moments
- free stream pressure and Mach number
- angle of attack
- nose radius (zero for a sharp nose tip)
- nose tip option,(sharp or blunt)

When utilizing the blunt nose additional cards have to be supplied which contains the pressure data for the spherical cap. This is accomplished by providing the location (x and y coordinates) for each point on the sphere at which the pressure has been determined, as calculated by the blunt body program, BLNT-2D.

Input to STRMLN and PLOT are being revised.

Outputs Obtained From All Programs

Program CONE

First, the remainder of the free stream (flight) conditions are given, including temperature, density, sound speed and Mach number together with the input values of static pressure and enthalpy and velocity.

The integrated internal and external mass flow, the change in shock angle, and the difference between the actual free stream stagnation enthalpy and the internally computed value, are all given as a check on the accuracy of the results. The shock shape is also given.

The flow parameters determined at points on the surface and in the shock layer, all around the body, include:
pressure (nondimensionalized with respect to free stream pressure),
density (nondimensionalized with respect to free stream density),
velocity components in all three directions,
entropy, and
Mach number

Program BLNT-2D

BLNT

The remainder of the free stream (flight) conditions are given, and are identical to those provided by Program CONE, described previously.

The flow parameters determined in the flow field are also identical with those given by Program CONE. However, three additional parameters are given. They are:
sound speed,
static enthalpy, and
ratio of specific heats (gamma).

2D

The output of the 2D subroutine is a characteristic net for which the same parameters as those obtained by BLNT are given. A mass flow parameter is also provided.

Program ROTAX

The output consists of the 2D characteristic net rotated to body axis, and a starting line for Program 3DMOC - BLUNT. Only five of the variables on this line are printed out. However, this starting line is repeated in Program 3DMOC - BLUNT at output stop 0, where all of the parameters indicated in the 3DMOC output list below are given.

Program 3DMOC

The program provides inviscid flow field information around the vehicle at any axial location (i.e. station). It also provides this same information in the shock layer (at points between the vehicle surface and the shock wave). Specifically, the following flow parameters are determined at each point in the flow field:
sound speed,
entropy,
pressure (nondimensionalized with respect to the free stream pressure),
pressure (dimensional - p.s.f.)
pressure coefficient - C_p
total pressure (ratio of the local to the free stream total pressures),
density (nondimensionalized with respect to the free stream density),
density (dimensional - slugs/ft^3),
static enthalpy,
temperature (nondimensionalized with respect to the free stream temperature),
temperature (dimensional - degrees Rankine),
real gas factor - Z,
ratio of specific heats - gamma (equilibrium air),
Mach number,
velocity in all three directions,
total velocity (vector),
dynamic pressure, and
mass flow ratio - presently being added

Program BUNLAY

The boundary layer properties determined, at all axial stations for all of the meridianal planes around the body, are as follows:
boundary layer thickness,
displacement thickness,
momentum thickness,
Reynolds number based upon momentum thickness,
wall (surface) enthalpy and temperature,
skin friction coefficient and heat transfer coefficient ($N_u/2R_e$), and
the boundary layer edge conditions including :
- density,
- pressure,
- Mach number,
- velocity, and
- entropy.

The following distributions within the boundary layer (including the body surface and boundary layer edge properties), are also given:
velocity,
static enthalpy,
stagnation enthalpy,
density, and
temperature.

Program AEROCO

This program determines the aerodynamic coefficients for the vehicle including:
C_L - lift coefficient,
C_D - drag coefficient,

C_N - normal force coefficient,
C_A - axial force coefficient,
C_M - moment coefficient,
X_{cp} - center of pressure, and
L/D - lift to drag ratio

Also, a running total of these parameters are given as a function of the vehicle axial station. The corresponding windward and leeward pressure distributions are also tabulated.

Program STRMLN

This program determines the location of streamlines both on the vehicles surface and out in the shock layer, and provides the values for the static pressures and velocities (in all three directions)along these streamlines.

Program PLOT

There is no print out supplied by program PLOT (plots only).

Results

L-V Haack-Cylinder

Three-dimensional flow fields were generated for an L-V Haack-cylinder configuration with an L/D = 3.0, at M=2.5 and M=3.0,at zero and five degrees angle of attack. Information obtained from these flow fields include the flow parameters around the body and in the shock layer, at the body stations in the vicinity of the propulsion system inlets. Inviscid static and total pressure distributions around the body, P vs. θ (where θ is the meridianal angle), at all points between the body and the shock at the inlet station, were obtained.

Results for the boundary layer characteristics at M=3.0, 40 KFT, α =5° are presented in Figure 2, for two body stations, as a function of the meridianal angle θ .

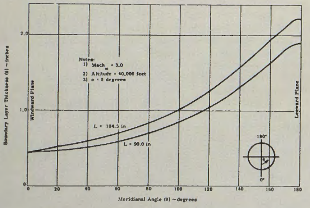

Figure 2 - Boundary Layer Thickness

Two stations are presented so that one can obtain some insight to the growth of the boundary layer as a function of body length and meridianal angle.

The boundary layer thickness on the windward side was 0.44 inches, and nearly independent of body length at these stations. (This result was also obtained for the M=2.5, 20 KFT, α =5° flight condition). The boundary layer thickness on the leeward side was 1.9 inches at station 90, and 2.2 inches at station 104.5 (an increase of approximately 15%). The value of the boundary layer thickness on the leeward side for the M=2.5 flight condition at station 90 was approximately 2.1 inches (an increase of approximately 10% over the corresponding value at M=3.0).

The boundary layer thickness as a function of body station is shown in Figures 3 and 4, for the windward and leeward planes respectively.

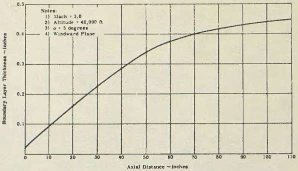

Figure 3 - Boundary Layer Thickness, Streamline No. 1, Windward Plane

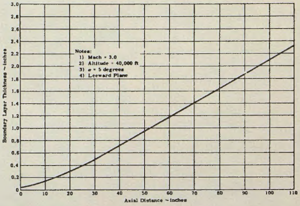

Figure 4 - Boundary Layer Thickness, Streamline No. 10, Leeward Plane

The displacement thickness varied between 0.15 inches to 0.675 inches for the windward and leeward planes respectively, at station 104.5. The corresponding values for the momentum thickness were 0.036 inches and 0.175 inches.

The properties in the boundary layer for the flow fields generated were also obtained. The profiles for the velocity, density, temperature, static enthalpy and total enthalpy distributions in the boundary layer at the leeward plane were obtained for the M=2.5, α =5° case. The velocity distribution is shown in Figure 5.

The degree of flow angularity to the inlet side wall was obtained so as to determine the degree of flow expansion there. The appropriate body streamline was traced as a function of body station and meridian angle as shown in Figure 6.

L-D Haack Cylinder

Inviscid three dimensional flow fields were generated for an L-D Haack-cylinder configuration with an L/D = 3.0. Data was obtained at free stream Mach numbers M = 2.5 and M = 3.0, at angles of attack of zero and five degrees, and at altitude of 40,000 feet. The information obtained from these flow fields include boundary layer thickness for sizing diverter heights, an indication of flow angularity around the missile skin, and velocity distributions in the boundary layer.

The boundary layer thickness was determined as a function of meridianal angle (around the body) for a range of stations in the area of interest (propulsion system inlet location). For the $M = 3.0, \alpha = 5$ flight conditions, at 95.3", the boundary layer thickness was 0.63 inches at $\theta = 45°$ and 1.37 inches at $\theta = 135°$. For the $M = 2.5, \alpha = 5$ flight conditions, at a comparable station (93.3"), the boundary layer thickness was just slightly lower than the Mach = 3 flight condition at $\theta = 45°$, but was 0.12 inches lower at $\theta = 135°$. Thus the boundary layer thickness is lower at the lower Mach number. This result is what one would expect and is a consequence of the lower Reynolds number due to the more severe over-expansion at the higher Mach number. (The pressure and density are lower and the temperature is higher.) Both the windward and leeward plane boundary layer thichnesses were determined. It is interesting to note that although the leeward boundary layer thicknesses are higher for the higher Mach number, the boundary layer thicknesses are approximately equal on the windward side.

An indication of the degree of flow angularity on the missile skin was obtained. Streamlines were traced downstream as they wrapped themselves around the missile body. The flow deflection angle β from the missile longitudinal axis is obtained from the slope of the streamlines: $\beta = \tan^{-1}(R\Delta\theta/\Delta z)$, where R is the body radius (10 inches) and $\Delta\theta$ and Δz are measured. It can be seen that the flow angularity is lower at the lower Mach number.

The boundary layer velocity profiles at the propulsion system inlet location for both Mach numbers were determined. The flow was assumed to be turbulent over the body. However, the laminar sublayer was clearly evident.

Additional data for other missile configurations will be presented at the symposium.

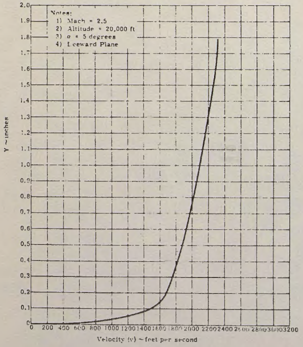

Figure 5 - Boundary Layer Velocity Profile

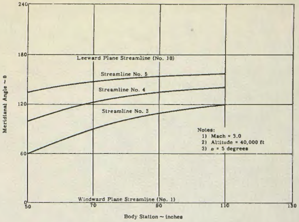

Figure 6 - Flow Angularity

Capabilities

This system of programs has been utilized successfully to calculate both perfect and real gas flow fields and aerodynamic coefficients. These calculations were conducted for many missile configurations in the Mach number regime from 2.0 to 11.0, at altitudes between sea level and 80,000 ft., and at angles of attack from 0 to 15 degrees.

Limitations

At high angles of attack, viscous phenomena predominate on the leeward side of the vehicle and incipient separation occurs. At present the inviscid 3DMOC program can not handle this situation.

At present, a vehicle's configuration must be described by a series of several cone frustums. Since the body is not represented by a smooth surface, it noticably affects the flow field results. Also, flares, or compression corners, can not be accommodated.

No boundary layer analysis or computer program is available to handle the boundary layer calculation for sharp nosed vehicles. Also, the calculation for the boundary layer properties for blunt nosed vehicles is a real gas analysis only. Errors are introduced into these calculations when perfect gas calculations are actually warranted.

The blunt body program BLNT-2D does not operate at Mach numbers less than 2.5, with the present calculational mesh size. However, it is felt that this problem may be alleviated by changing this mesh size.

Conclusions

It is felt that this system of programs provides the basis for a unique and effective tool which is necessary for the advancement of technology in aerospace research, design and development of missiles, rockets, reentry vehicles and spacecraft.

Future Work

The areas of future work to improve this system of programs are as follows:
An improved geometry capability so as to be able to handle smooth bodies (described by equations) or nearly smooth bodies (approximated by many cone frustums), with flares.

A perfect gas boundary layer calculation for blunt bodies.
Checkout and further development of Program STRMLN.
Development of an all purpose automatic plotting program to obtain graphically all of the significant results obtained with this system of programs.

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