

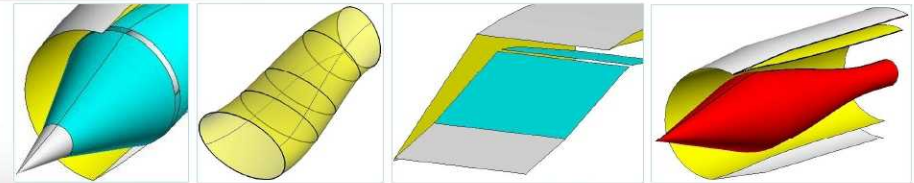
DESIGN AND ANALYSIS TOOLS FOR SUPERSONIC INLETS

Computational tools are being developed for the design and analysis of supersonic inlets. The objective is to update existing tools and provide design and low-order aerodynamic analysis capability for advanced inlet concepts. The Inlet Tools effort includes aspects of creating an electronic database of inlet design information, a document describing inlet design and analysis methods, a geometry model for describing the shape of inlets, and computer tools that implement the geometry model and methods. The geometry model has a set of basic inlet shapes that include pitot, two-dimensional, axisymmetric, and stream-traced inlet shapes. The inlet model divides the inlet flow field into parts that facilitate the design and analysis methods. The inlet geometry model constructs the inlet surfaces through the generation and transformation of planar entities based on key inlet design factors. Future efforts will focus on developing the inlet geometry model, the inlet design and analysis methods, a Fortran 95 code to implement the model and methods. Other computational platforms, such as Java, will also be explored.



Design and Analysis Tools for Supersonic Inlets

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Background



Objective: Develop computational tools for the aerodynamic design and analysis of supersonic inlets.

Some key points:

- Supersonic inlet aerodynamics involves flow compression, flow deceleration, shock waves, turbulent boundary layers, shock / boundary layer interactions, separated flow, flow control, etc...
- Goals are to maximize total pressure recovery, limit total pressure distortion, and limit inlet drag.
- Various efforts for supersonic inlet design have yielded a number of computer programs and tools for inlet design over the decades (IPAC, InletMOC, LercInlet, LAPIN).
- New inlet concepts and new computational capabilities have prompted us to re-visit our supersonic inlet design tools and start developing new tools.
- These tools should perform low-order analysis methods while also providing inputs useful for higher-order CFD methods.
- This has led to the ***Inlet Tools*** effort.

Four Aspects of the Inlet Tools effort

1. Inlet Tools Electronic Database
2. Inlet Design and Analysis Document
3. Inlet Geometry Model
4. Inlet Tools (computer codes)

1) Inlet Tools Electronic Database

- Database contains various information within the public domain related to inlets and inlet aerodynamics:
 - Papers, reports, and other literature (NACA, NASA, etc...)
 - Software source code, worksheets, or programs (code distribution mechanism)
 - Data on inlet analysis and testing
- Database is stored on a Web-based eRoom (i.e. a file cabinet on the Internet).
- Members must be invited by the eRoom coordinator (John Slater).
- Access is controlled through an member account with login ID and password.
- Members can create folders and upload files to contribute information to the eRoom.
- Available as a central resource.



2) Inlet Design and Analysis Document



- Document that describes the aerodynamics and operation of inlets and how they are modeled, analyzed, and designed.
- Intent of the document is to provide sufficient background and an outline of the methods that are then coded in the Inlet Tools.
- The document is in the form of a MS Word document.
- While the Inlet Tools may be implemented in various platforms and coding styles, the basic theory and description of the methods are contained within the document.
- Interested individuals are welcome to help write, edit, or comment on the document as it is being created.

Inlet Tools Document

Introduction
Inlet Operation
Parts of the Inlet Flowfield
Airflow
Performance Measures
Inlet Geometry Model
Analysis Methods
Design Methods
Appendices
 Equation of State and Gas Models
 Standard Atmosphere and Disturbances
 Flow Rates
 Compressible Flow
 Conical Flow
 Boundary Layers
 Bleed and Bypass Flows
 Flow Control
 Method of Characteristics Methods
 Quasi-One-Dimensional Methods
References

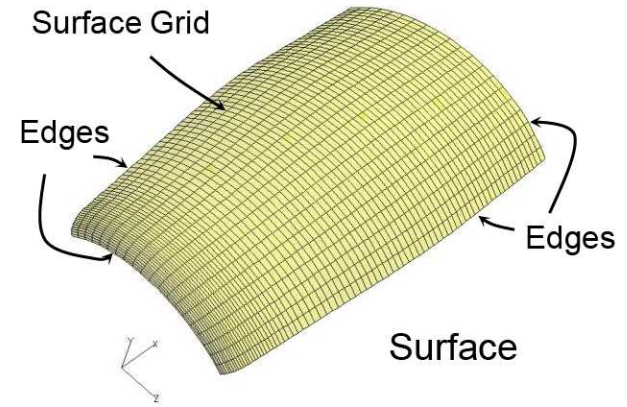
3) Inlet Geometry Model

- The **Inlet Geometry Model** describes and parameterizes the shape of the various inlets of interest for the Inlet Tools.
- A set of **Basic Inlet Shapes** defines the scope of possible geometries.
- The inlet flow field is divided into **Parts** that further helps establish parameters for defining the geometry.

Example: A two-dimensional inlet shape for an external supersonic diffuser has ramps defined by angles.

- The Inlet Geometry Model consists of a patchwork of **Surfaces**.
- Each surface is constructed from **Edges** defined on a plane.
- Each edge is defined by one or more planar **Entities**.
- The model allows inlet variable geometry elements such as translating and rotating inlet components.
- Grid points are generated on the edges and surfaces to produce CFD-quality surface grids.

- Basic Inlet Shapes**
- Flush
 - Pitot
 - Two-dimensional
 - Axisymmetric
 - Stream-traced
 - Duct



- Parts of the Inlet Flow Field**
- Freestream
 - Approach Flow
 - Nose
 - External Supersonic Diffuser
 - Cowl Lip
 - Cowl Exterior
 - Internal Supersonic Diffuser
 - Throat
 - Isolator
 - Subsonic Diffuser
 - Engine Face



4) Inlet Tools

- The Inlet Tools will be computer programs that performs some operation documented in the Design and Analysis Document and describes the inlet in using the Inlet Geometry Model.
- Various computer languages / platforms are possible (Fortran 95, Python, C, MatLab, etc...).
- Current Inlet Tool development:
 - Fortran 95.
 - Text-based input and output files (Plot3d format for surface grids).
 - Incorporate the analysis capabilities of IPAC (Inlet Performance and Analysis Code) to determine: a) Flow rates, b) Total pressure recovery, and c) Inlet drag.
 - Incorporate MOC and Quasi-1D CFD methods (InletMOC, LerInlet, LAPIN).
 - Incorporate design methods for inlet sizing, external and internal supersonic diffusers, Buseman-derived stream-traced inlets, etc...
- Explore other programming options (GUI, Python, etc...)

Basic Inlet Shapes of the Geometry Model



The Geometry Model is build upon a set of Basic Inlet Shapes that represent the past inlets and inlets of future interest.

Flush

The shape is flush with the vehicle body and directs vortices into the internal ducting.

Pitot

The shape has a circumferential cowl lip, which may be blunt or sharp. The circumferential shape may be round, rectangular, D-shaped, or scarfed. The circumference may be partial and the shape may be integrated into the body.

Two-Dimensional

The shape is created by extruding a planar profile in the cross-stream direction. Sidewalls may be used to contain the compression. Flow paths may be split or bifurcated.

Axisymmetric, Outward-Turning

The shape is created by rotating a profile about an axis-of-symmetry. The profile turns the supersonic flow outward from the axis. The shape can be the full or partial annulus with sidewalls.

Axisymmetric, Inward-Turning

The shape is created by rotating a profile about an axis-of-symmetry. The profile turns the supersonic flow toward the axis. The shape can be the full or partial annulus with sidewalls.

Stream-Traced

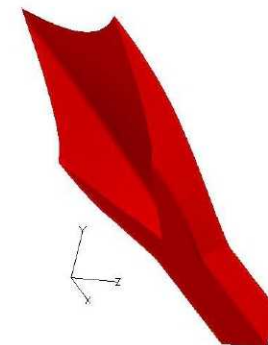
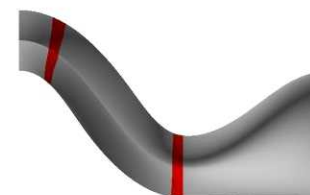
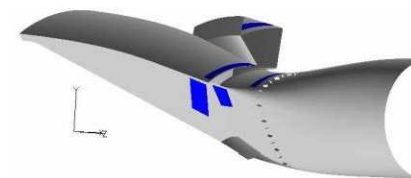
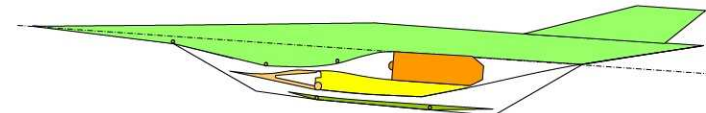
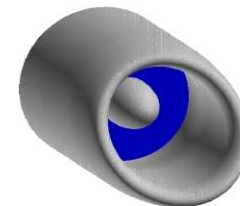
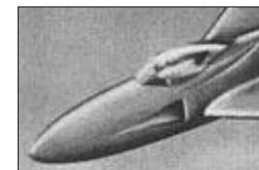
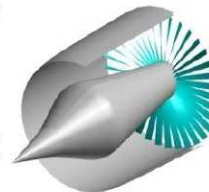
The shape is created from tracing a throat or capture area outline through a conical Busemann flowfield. Traced shapes can be truncated to shorten blended for shape transition.

Ducts

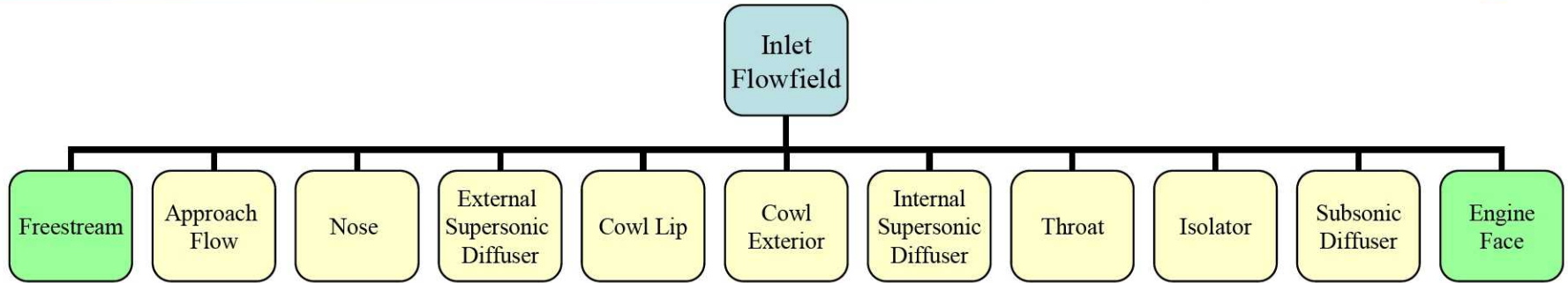
The shape is an internal duct. Subsonic diffusers, S-ducts, isolators, transition ducts.

Basic Inlet Shapes

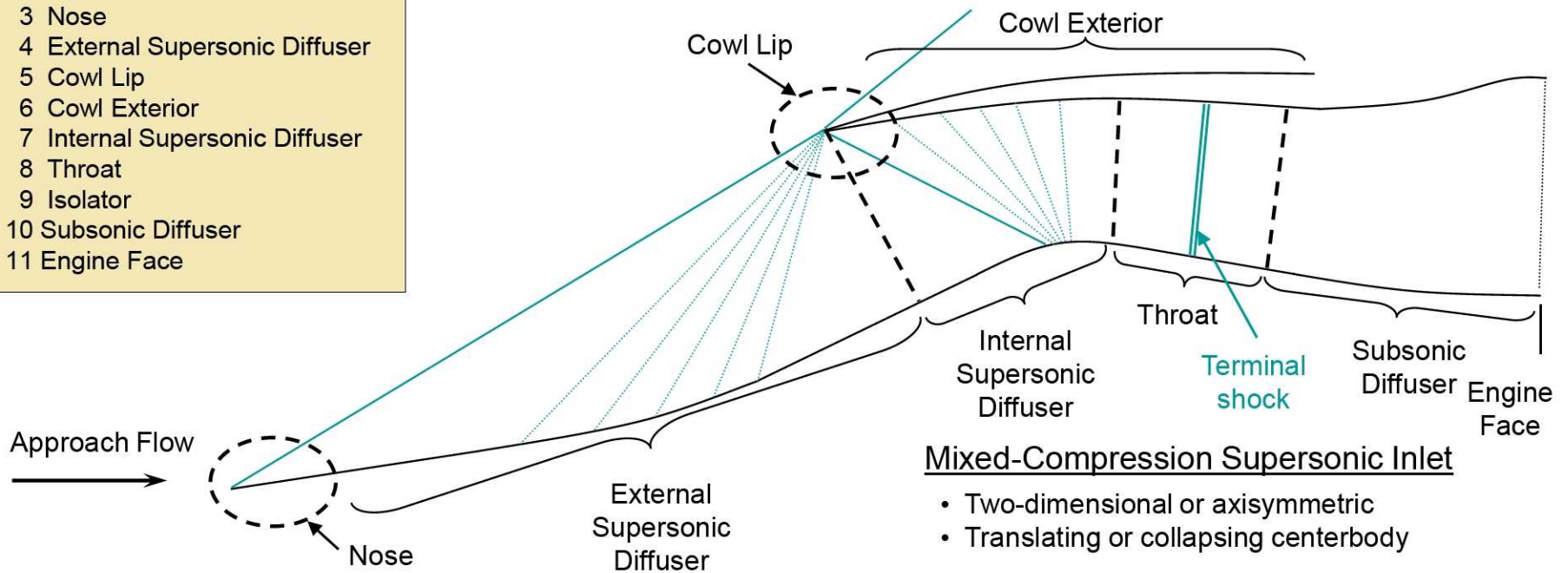
- 1 Flush
- 2 Pitot
- 3 Two-dimensional
- 4 Axisymmetric, Outward-Turning
- 5 Axisymmetric, Inward-Turning
- 6 Stream-traced
- 7 Duct



Parts of the Inlet Flow Field



- Inlet Flow Field Parts**
- 1 Freestream
 - 2 Approach Flow
 - 3 Nose
 - 4 External Supersonic Diffuser
 - 5 Cowl Lip
 - 6 Cowl Exterior
 - 7 Internal Supersonic Diffuser
 - 8 Throat
 - 9 Isolator
 - 10 Subsonic Diffuser
 - 11 Engine Face



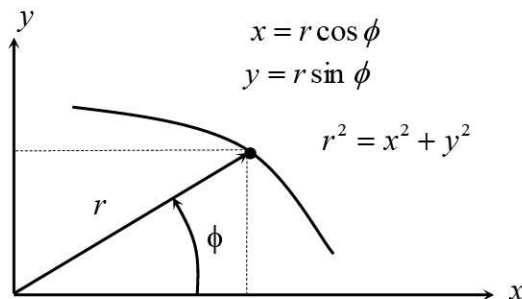


Edges and Basic Entities

- An **Edge** is defined by one or more **Entities** that are connected end-to-end.
- The planar curves are defined in a Cartesian (x,y) coordinate system or a cylindrical (r,ϕ) coordinate system.
- Each curve has a one-dimensional coordinate s that corresponds to the distance along the curve with the length of the curve denoted as s_{max} .
- The coordinate s can be normalized by s_{max} to form s^* .
- Each entity requires certain geometry inputs (e.g. angles, lengths, ...)
- Grid points for CFD are distributed along the entities using key grid spacings and grid point densities.
- The entities are then rotated, translated, and / or mirrored to place them into an edge in the Cartesian (x,y,z) coordinate system.

Basic Entities

- 1 Line
- 2 Circle
- 3 Ellipse
- 4 Rectangle
- 5 Super-ellipse
- 6 Polynomial
- 7 Piecewise linear curve
- 8 Cubic spline curve
- 9 NURBS curve
- 10 4-Point NURBS curve

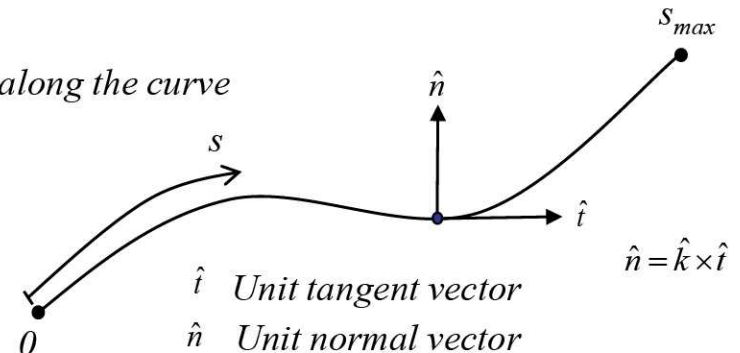


s_{max} Distance along the curve

$$0 \leq s \leq s_{max}$$

$$s^* = s / s_{max}$$

$$0 \leq s^* \leq 1$$

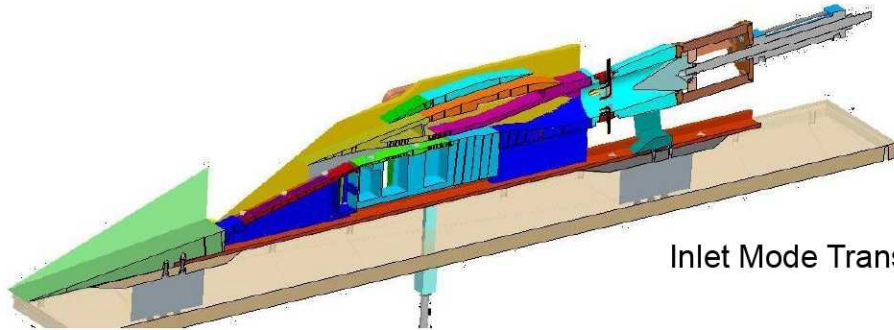


Surface Definition: Sweeping

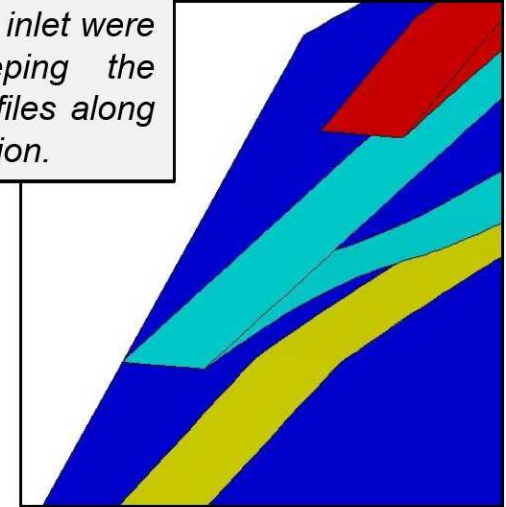


1. Curvilinear Sweeping: An edge is swept along a guiding line or curve.

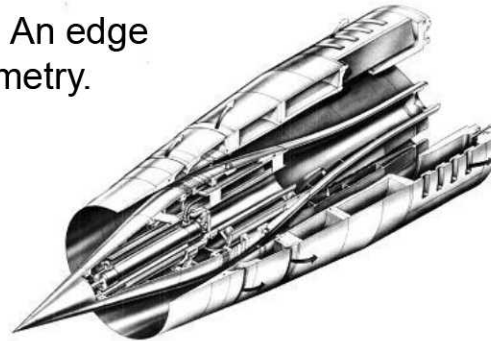
Example: The forward surfaces of the IMX inlet were defined by sweeping the ramp and cowl profiles along a line in the z-direction.



Inlet Mode Transition (IMX) Inlet

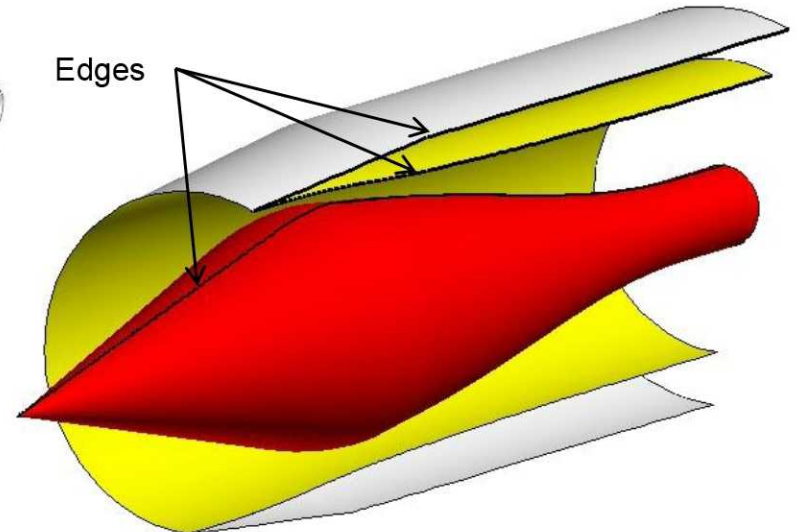


2. Axisymmetric Sweeping: An edge is swept about an axis-of-symmetry.



NASA 40-60 Inlet

Example: The surfaces of the NASA 40-60 inlet were defined by sweeping the centerbody and cowl profiles about the axis-of-symmetry.

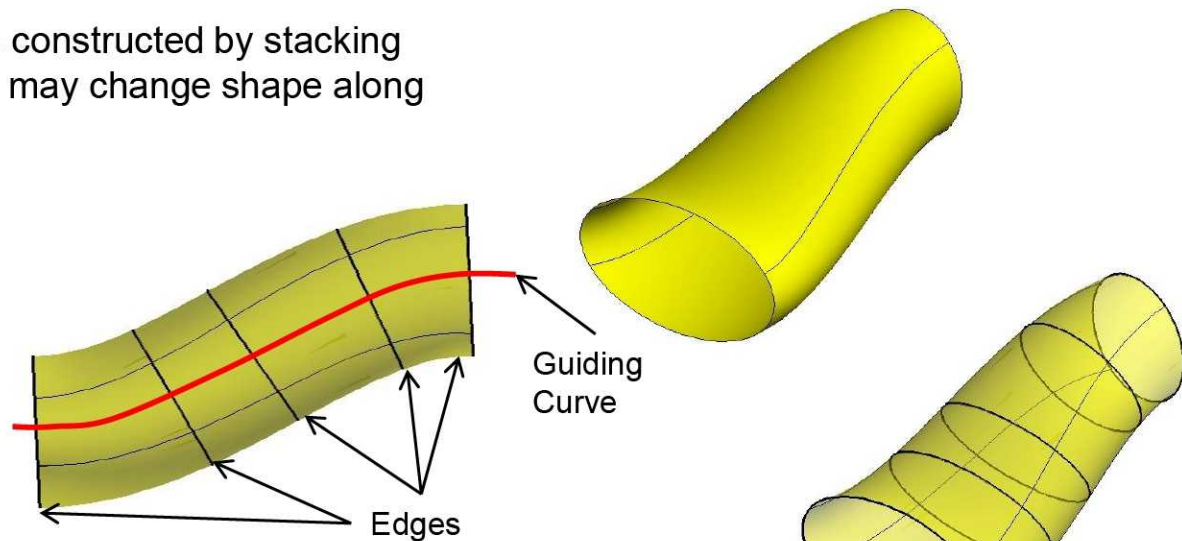


Surface Definition: Stacking

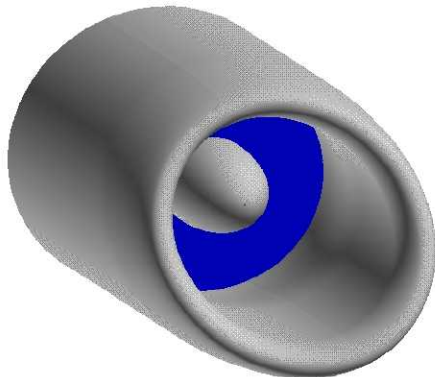


3. Curvilinear Stacking: A surfaces is constructed by stacking edges along a guiding curve. The edge may change shape along the guiding curve.

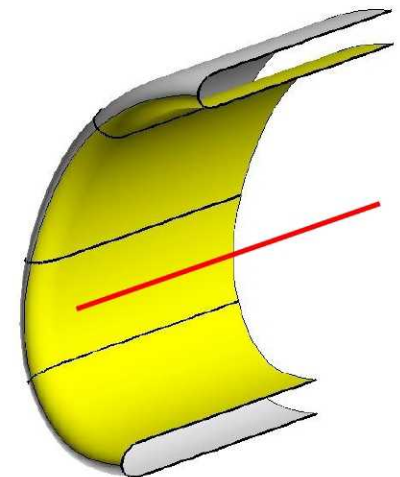
Example: The surfaces of a subsonic duct were defined by stacking edges along a guiding curve. The edges consist of super-ellipses that change in the aspect ratio along the guiding curve



4. Rotational Stacking: A surface is constructed by stacking edges about an axis. The edges are defined on circumferential planes and may change shape about the axis.



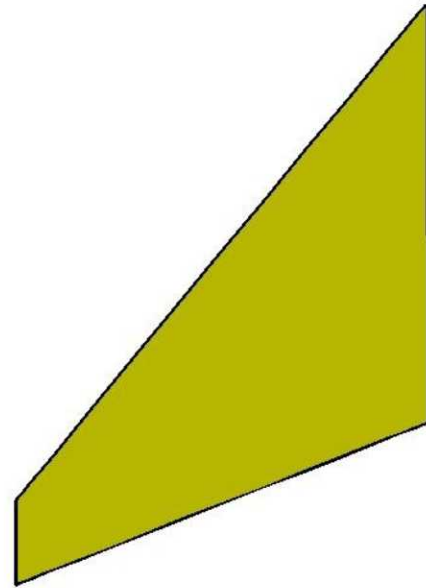
Example: The surfaces of a scarfed inlet were defined by stacking edges about an axis. The edges consist of super-ellipses for the cowl lip and lines for the aft cowling. The shape of the highlight and the forward projection of the cowl lip vary about the axis.



Surface Definition: TFI and Analytic

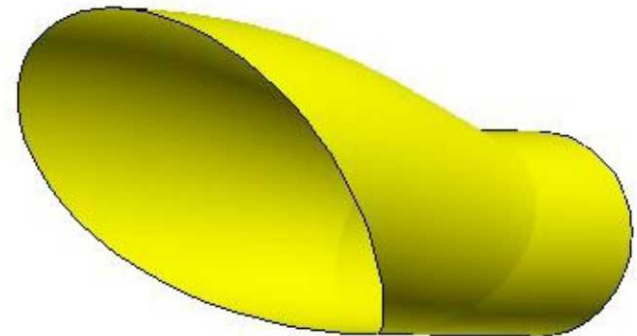
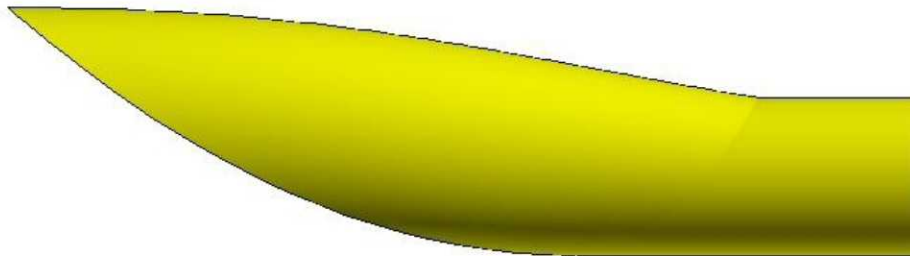
5. Transfinite Interpolation: A surface is constructed using a bi-linear interpolation between four edges in a plane that bound the surface.

Example: The surfaces of a sidewall for a two-dimensional inlet were defined by interpolation of the four edges.



6. Analytic: A surface is constructed using other analytic or computational methods.

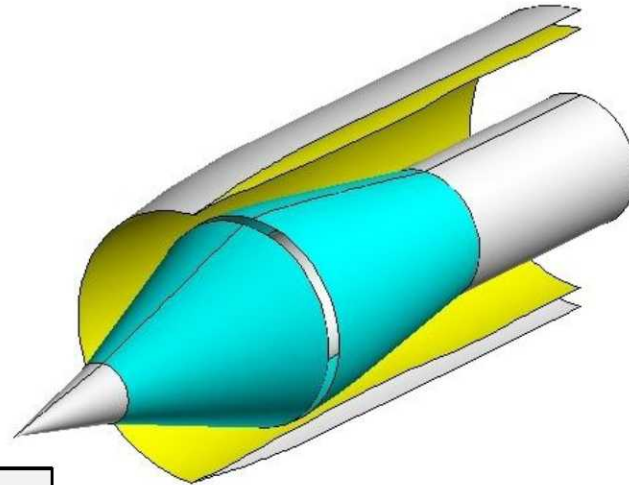
Example: The surfaces of a stream-traced inlet were defined by tracing the streamlines of a Busemann flowfield using a circular edge at the outflow.



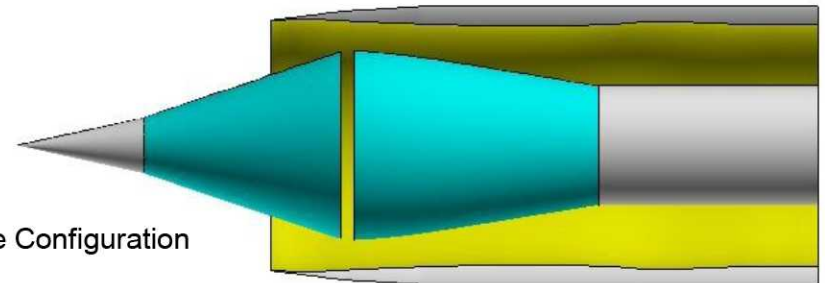
Variable Geometry



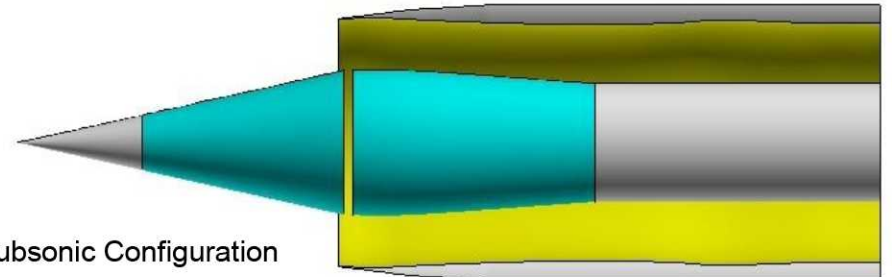
NASA Variable Diameter Centerbody (VDC) Inlet



Example: The VDC inlet has centerbody surfaces that can partially collapse and translate to vary the cross-sectional area of the inlet. The edges for the inlet profile are specified to rotate about a point and translate in the axial direction.



Cruise Configuration



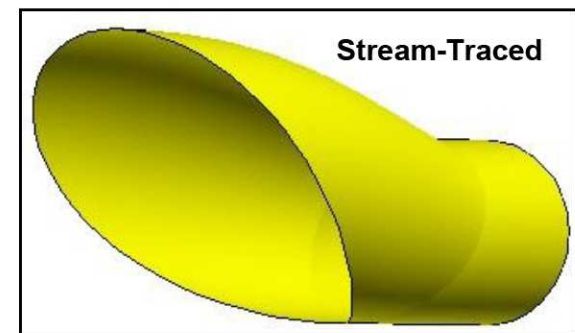
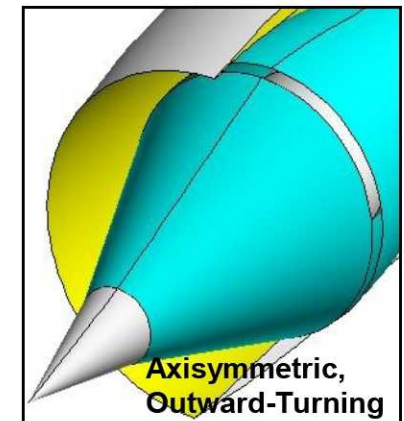
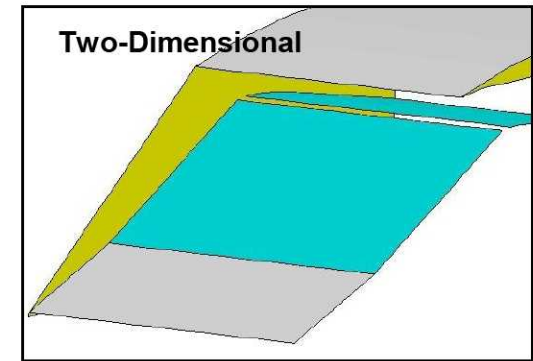
Subsonic Configuration

External Supersonic Diffuser



We desire to describe the inlet geometry model in terms of parameters associated with characteristics of the inlet. This is demonstrated through the example of an external supersonic diffuser...

- Inlet sizing requirements set the size of the capture area.
- Select a shape:
 - Two-dimensional
 - Axisymmetric Outward-Turning
 - Axisymmetric Inward-Turning
 - Stream-Traced
- The type of shape sets the radii, heights, widths, etc... of the capture area.
- The diffuser compresses and decelerates the incoming supersonic flow through turning and creation of Mach or shock waves.
- The diffuser is designed to create a certain Mach number, flow angle, or static pressure at the cowl lip.



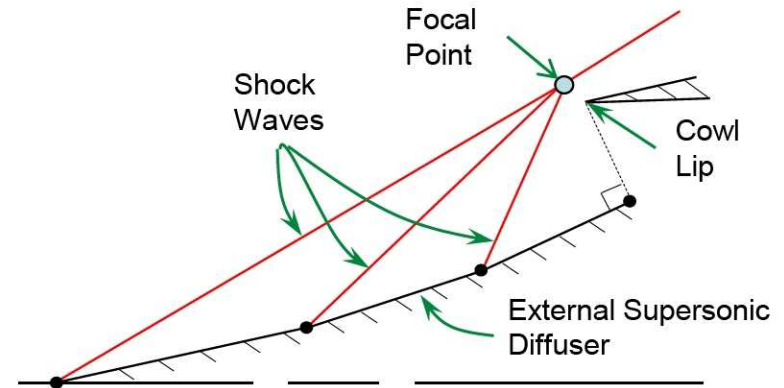
Parameters

M_0	Mach number at the inflow
M_1	Mach number at the cowl lip station
K	Type of diffuser shape
G	Dimensions of the capture area

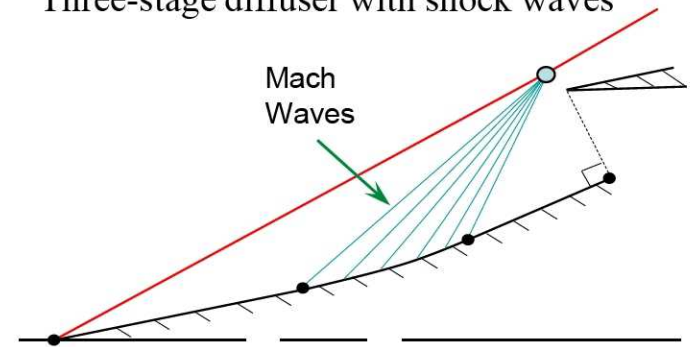
Stages, Waves, and Focal Points



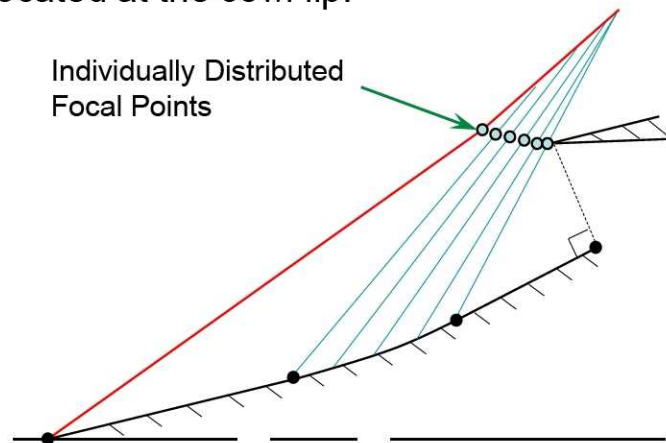
- Compression and deceleration occurs through a series of **Stages** involving the turning of the supersonic flow.
- A turn is characterized by a start point, end point, and a turning angle.
- A sharp turn has the start and end points coinciding and results in a shock wave.
- A smooth turn results in a Mach wave.
- Each shock or Mach wave originates at the start point of the turn and passes through a **Focal Point** near the cowl lip.
- The focal points may be coincident or distributed depending on the design intent.
- A minimum-length diffuser would have coincident focal points located at the cowl lip.



Three-stage diffuser with shock waves



Three-stage diffuser with smooth turning



Parameters

N_s	Number of stages
K_s	Type of stage (=0 sharp, =1 smooth)
θ_i	Turning angle of stage i
N_F	Number of focal points
$(x_s, y_s)_i$	Coordinates of the start of the stage
$(x_F, y_F)_i$	Coordinates of the focal points

Nose, Leading Edge, and Sidewall

- The external supersonic diffuser starts at the *nose* (point) or *leading edge*.
- The nose or leading edge can be sharp or circular and blends into the angle of the first stage.

Parameters

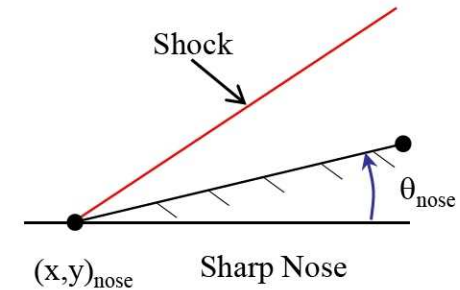
K_{nose}	Type of nose (=0 sharp, =1 circular)
θ_{nose}	Turning angle at nose (stage 1)
$(x,y)_{nose}$	Coordinates of the start of the nose
r_{nose}	Circular radius of the nose

- If the capture shape is two-dimensional or a circumferential segment, then sidewalls are needed to contain the captured streamtube.

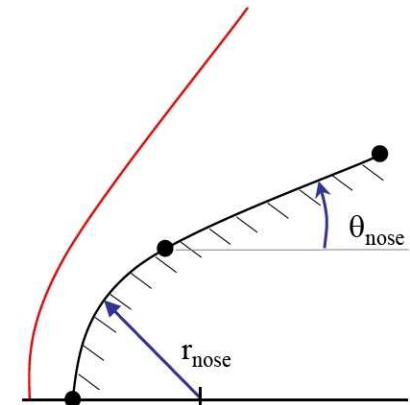
Parameters

$G_{sidewal}$	Coordinates of the sidewall surface
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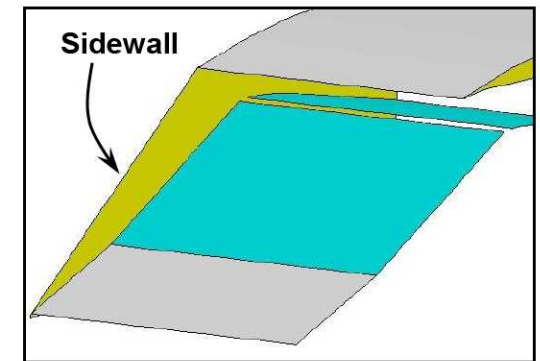
- From the flow conditions and the geometry parameters, the surfaces of the external supersonic diffuser can be constructed.
- The main objective is then to compute shock, Mach waves, pressures, flow velocities, etc... to determine the performance of the diffuser (total pressure recovery, drag, spillage, boundary layers, ...).
- Analytic methods (shock relations, Prandtl-Meyer flow, etc...), method of characteristics, and CFD can be used to compute the flow quantities.



$(x,y)_{nose}$ Sharp Nose



$(x,y)_{nose}$ Circular Nose

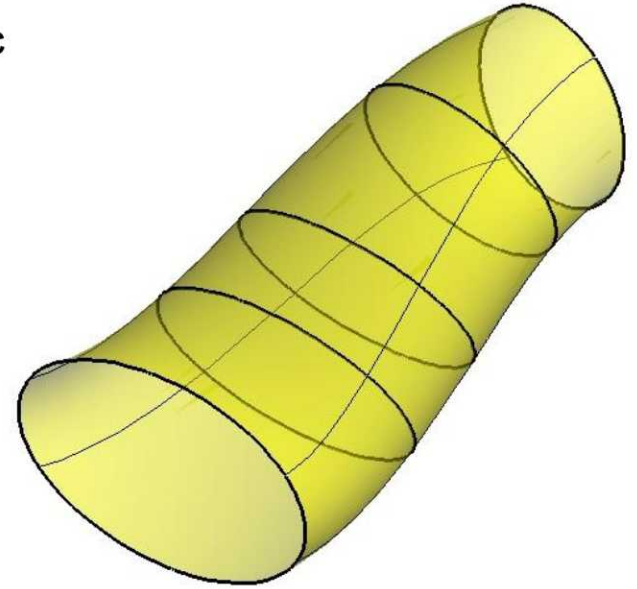


Subsonic Diffuser



Another example is the design and analysis of a subsonic diffuser...

- The subsonic diffuser is downstream of the throat and extends to the engine face.
- The diffuser must transition in cross-sectional shape and area to match the geometry at the throat and engine face.
- The flow conditions at the throat and engine face are specified.
- The flow compresses and decelerates through the expansion of the cross-sectional area.
- Area variation can be specified or determined by desired variations in Mach number or static pressure.
- Flow control devices may be present, such as vortex generators, bleed, bypass, etc...
- Geometry may be adjusted for boundary layer growth.
- The objective is to determine the flow properties to compute total pressure recovery, drag, distortion, etc...





Future Plans

- Continue the development of the Inlet Tools eRoom and the Inlet Design and Analysis Document.
- Continue the development of a Fortran 95 version of the Inlet Tool:
 - One researcher working at 50% FTE
 - Complete the development of the Inlet Geometry Model (Nov 2009)
 - Incorporate low-order analysis methods for design and analysis (IPAC) (Dec 2009)
 - Incorporate method-of-characteristics methods (InletMOC, Lerclnlet) (Mar 2010)
 - Incorporate quasi-one-dimensional CFD methods (LAPIN) (Jun 2010)
- Explore other programming options and platforms.
- Explore partnerships with other researchers and organizations to document and develop inlet tools.
- Contact: John.Slater@nasa.gov

