



External-Compression Supersonic Inlet Design Code

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A computer code named SUPIN has been developed to perform aerodynamic design and analysis of external-compression, supersonic inlets. The baseline set of inlets include axisymmetric pitot, two-dimensional single-duct, axisymmetric outward-turning, and two-dimensional bifurcated-duct inlets. The aerodynamic methods are based on low-fidelity analytical and numerical procedures. The geometric methods are based on planar geometry elements. SUPIN has three modes of operation: 1) generate the inlet geometry from an explicit set of geometry information, 2) size and design the inlet geometry and analyze the aerodynamic performance, and 3) compute the aerodynamic performance of a specified inlet geometry. The aerodynamic performance quantities include inlet flow rates, total pressure recovery, and drag. The geometry output from SUPIN includes inlet dimensions, cross-sectional areas, coordinates of planar profiles, and surface grids suitable for input to grid generators for analysis by computational fluid dynamics (CFD) methods. The input data file for SUPIN and the output file from SUPIN are text (ASCII) files. The surface grid files are output as formatted Plot3D or stereolithography (STL) files. SUPIN executes in batch mode and is available as a Microsoft Windows executable and Fortran 95 source code with a makefile for Linux.

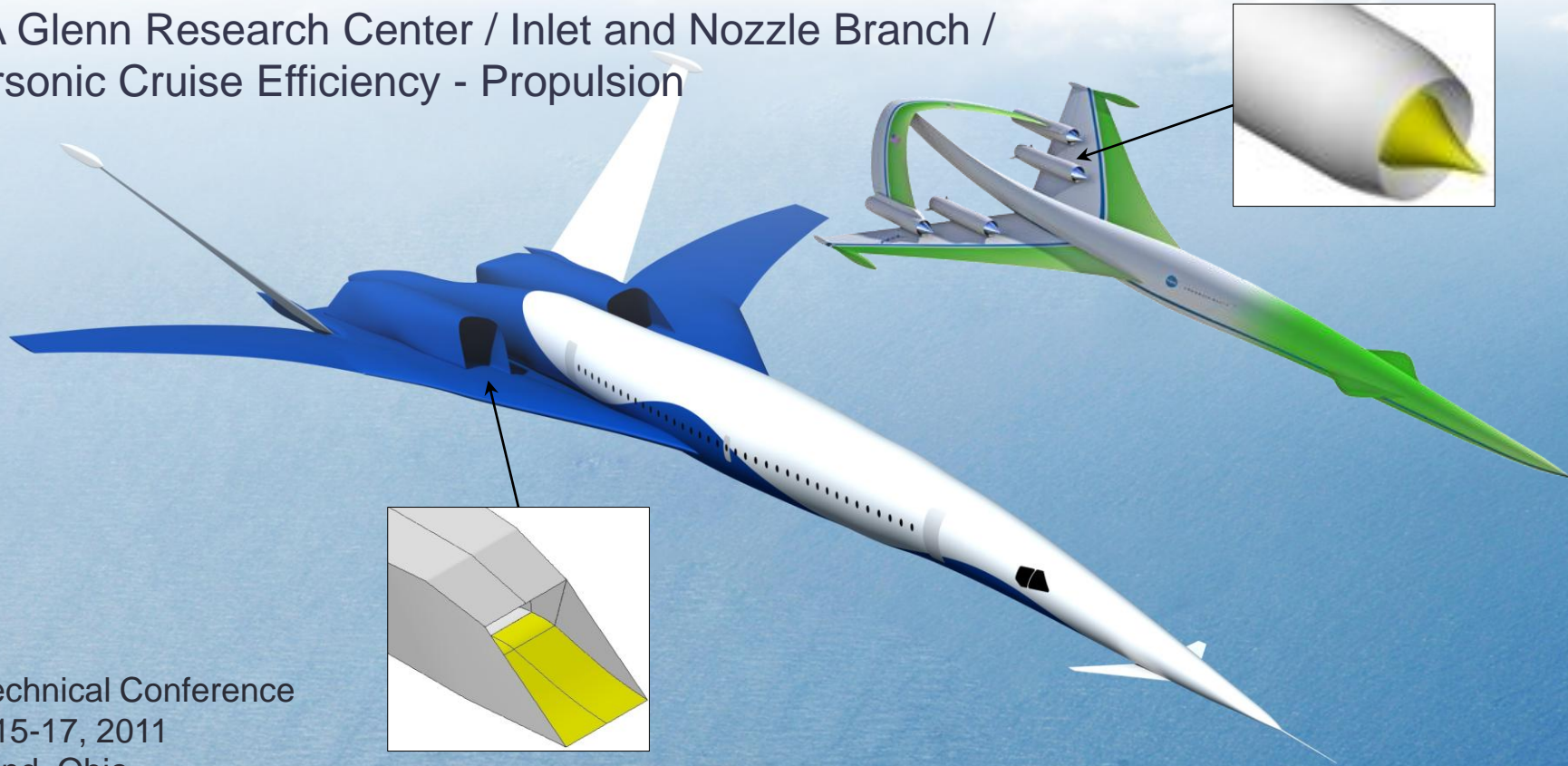


External-Compression Supersonic Inlet Design Code

Supersonics Project

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NASA Glenn Research Center / Inlet and Nozzle Branch /
Supersonic Cruise Efficiency - Propulsion



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Background



Goal: Develop computational tools to perform aerodynamic design and analysis of supersonic inlets to determine inlet geometry and performance.

Some key points:

- Supersonic inlet design methods have been developed over the last 60+ years.
- Various computational tools have been developed over the decades (IPAC, InletMOC, LercInlet, LAPIN) based on analytic, empirical, and computational methods.
- New computational frameworks (Java, Matlab, etc...) and new inlet concepts (stream-traced, advanced flow control, etc...) have prompted us to re-visit our supersonic inlet design tools and to develop new tools.
- The tools should perform low-fidelity analysis while also providing geometry for higher-fidelity, computational fluid dynamics (CFD) analysis.
- This has lead to the ***Inlet Tools*** effort of the Supersonic Project.
- Small-scale effort: the work discussed in this presentation has involved one researcher (John Slater) at $\frac{1}{2}$ full-time employee (FTE) for about 3 years.



Four Aspects to the Inlet Tools Effort

1. Inlet Tools Electronic Database

- Internet-based eRoom (access is controlled by member account with userid and password).
- Database stores files submitted by members.
- Database contains PDF files of public-domain papers, reports, and other literature.
- Location to store data, source code, input and output files.

Aspects of the Inlet Tools Effort

1. Electronic Database
2. Design and Analysis Document
3. Geometry Model
4. Computational Tools

2. Inlet Design and Analysis Documentation

- Documents fundamental aerodynamic design and analysis methods suitable for supersonic inlets.
- Provide background for methods coded into the computational tools.
- Document the inlet geometry model and computational tools.
- The document is in the form of a MS Word document.

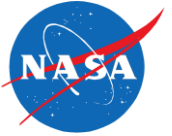
3. Inlet Geometry Model

- Describes supersonic inlet geometry in terms of basic parts and key geometric factors.
- Recognizes that some inlet geometry can be constructed from simple, planar entities.
- Provides framework for constructing surfaces for visualization and CFD analysis.

4. Computational Tools

- Implements the inlet geometry model and design and analysis methods into a computer program.
- Various frameworks can be used (Fortran 95, Java, Python, C++, Matlab, etc...)

SUPIN (SUPersonic INlet) Design Code

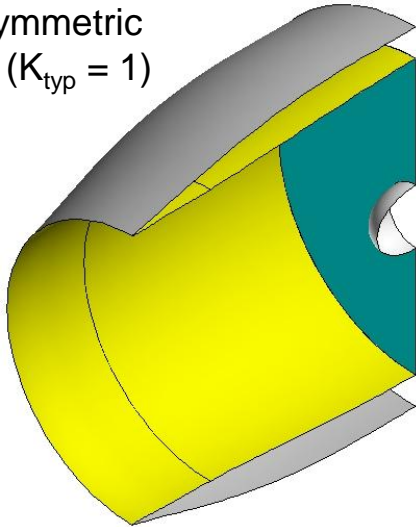


- Incorporates the supersonic inlet geometry model and design and analysis methods.
- Currently capable of design and analysis of external-compression, supersonic inlets (Mach 1.6-2.0).
- Written in Fortran 95 on Windows laptop.
- Text-based (ASCII) input data file with blocks and lines of input.
- Text-based (ASCII) output file containing inlet coordinates and performance properties.
- Creates surface and planar CFD grid files (ASCII Plot3d and STL formats).
- Single code with an Windows executable or source code and makefile for Unix / Linux systems.
- Modes of inlet design and analysis:
 - $K_{mode} = 1$. Generate the inlet geometry from an explicit set of geometry factors and inputs.
 - $K_{mode} = 2$. Perform design operations to size and generate the geometry of the inlet based on specified factors and inputs.
 - $K_{mode} = 3$. Perform aerodynamic analysis of an inlet defined from an explicit set of geometry factors and inputs.
- Primary inlet performance measures include:
 - Flow rates
 - Total pressure recovery
 - Inlet drag
- Inlet aerodynamics also includes total pressure distortion, stability (buzz), etc...

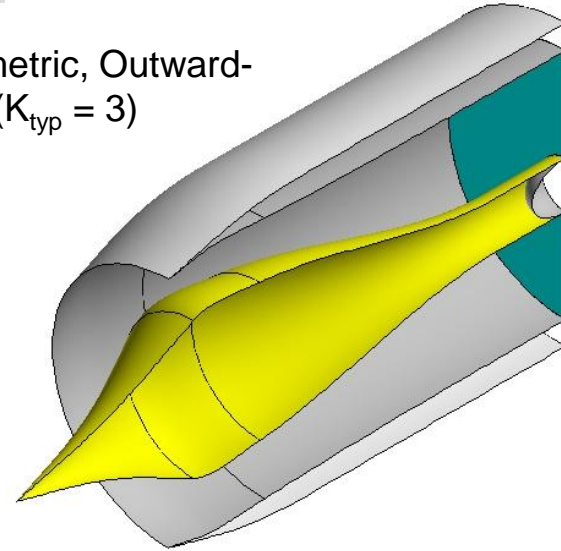
Baseline Inlet Shapes



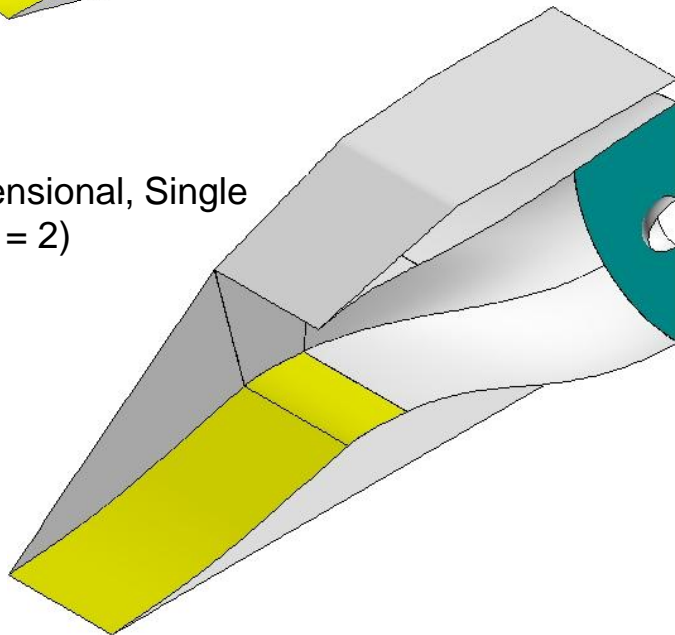
Axisymmetric
Pitot ($K_{typ} = 1$)



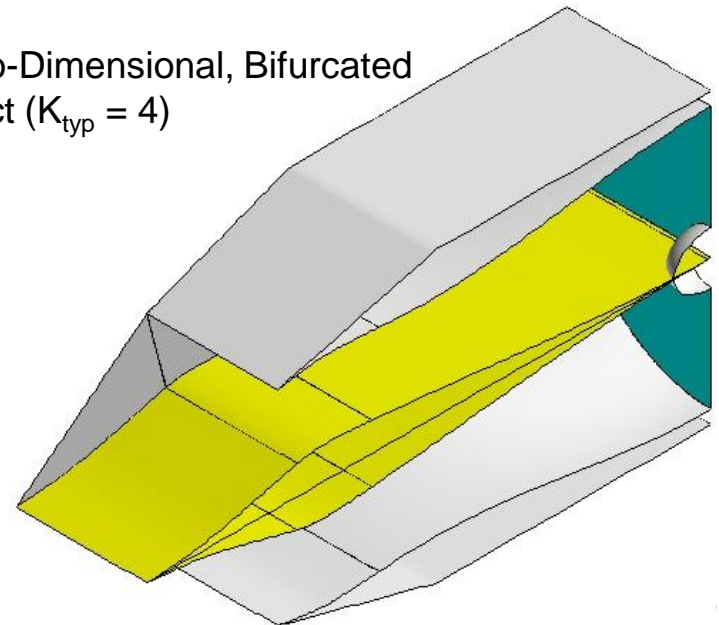
Axisymmetric, Outward-
Turning ($K_{typ} = 3$)



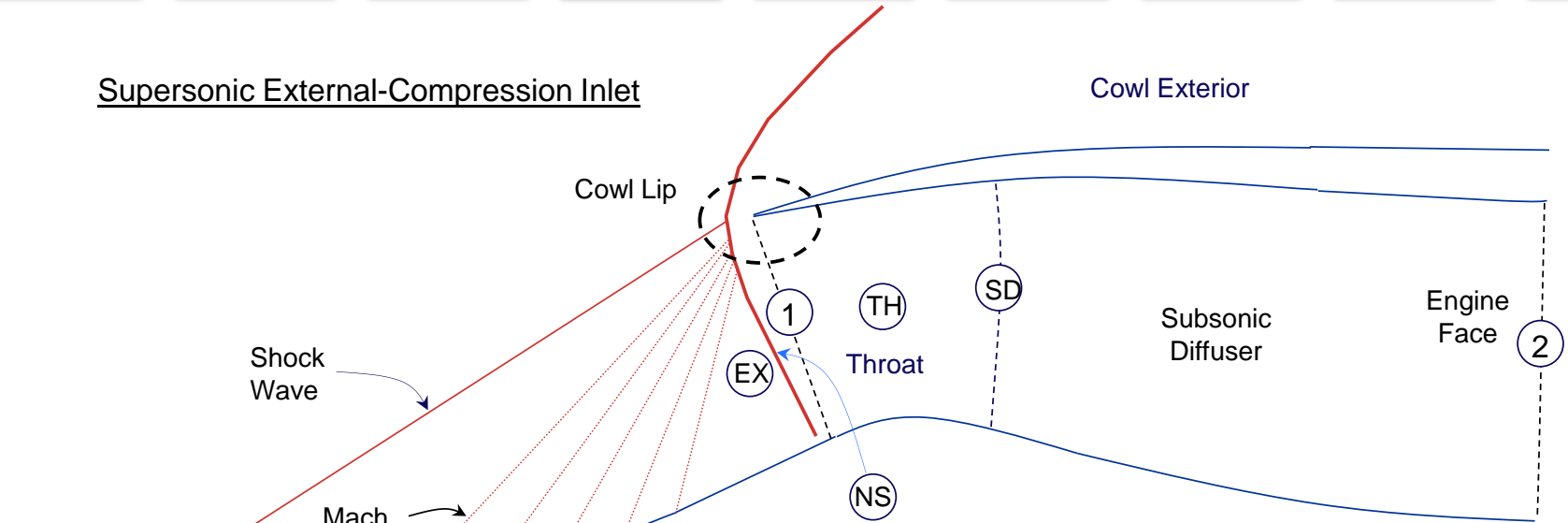
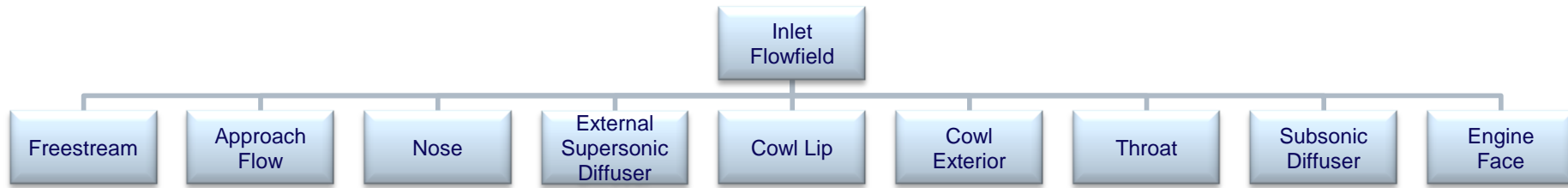
Two-Dimensional, Single
Duct ($K_{typ} = 2$)



Two-Dimensional, Bifurcated
Duct ($K_{typ} = 4$)



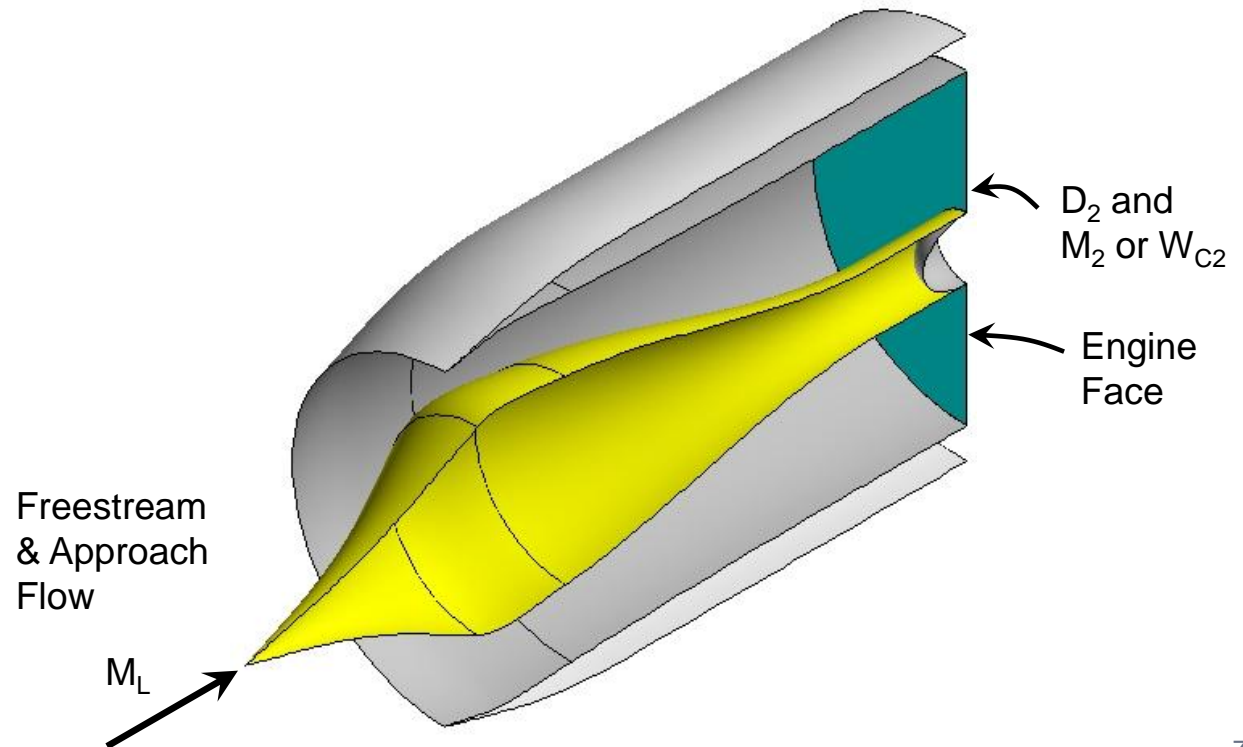
Parts of the Inlet Flow Field



Station	Description
0	Freestream
L	Just upstream of the inlet
EX	Just upstream of the normal shock
NS	Just downstream of the normal shock
1	Entrance to interior duct at the cowl lip
TH	Throat (minimum cross-sectional area)
SD	Start of the subsonic diffuser
2	Engine face

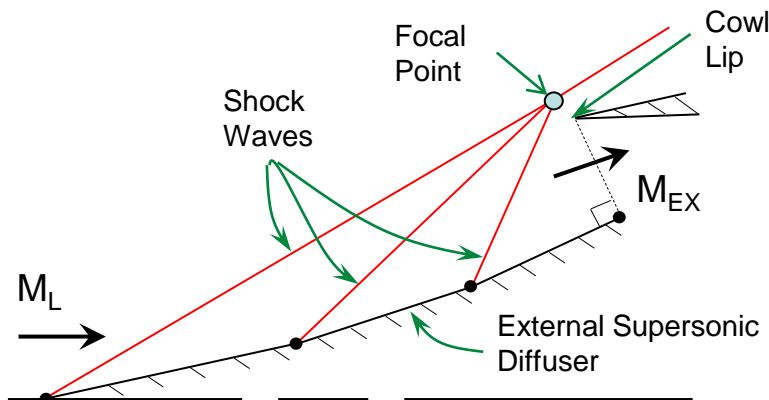
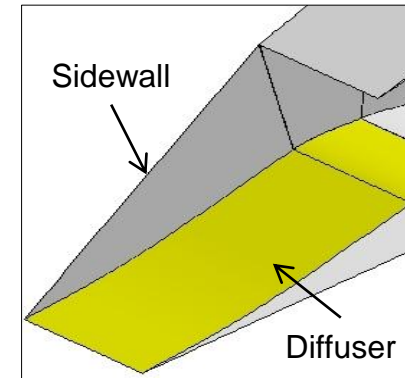
Freestream, Approach Flow, Engine Face

- **Freestream** conditions are known from aircraft mission (Mach number, altitude).
- The **Approach Flow** involves state changes (compression, expansion) due to flow over the forward part of the aircraft. Station L has uniform flow just upstream of the start of the inlet.
- The **Engine Face** geometry and conditions (Mach number, corrected flow rate) are known as part of the aircraft and propulsion system design process.
- Engine is a turbo-fan engine that typically operates at a constant corrected flow. For M_L approaching Mach 1.8, the engine may reach limits that reduce the corrected flow rate.

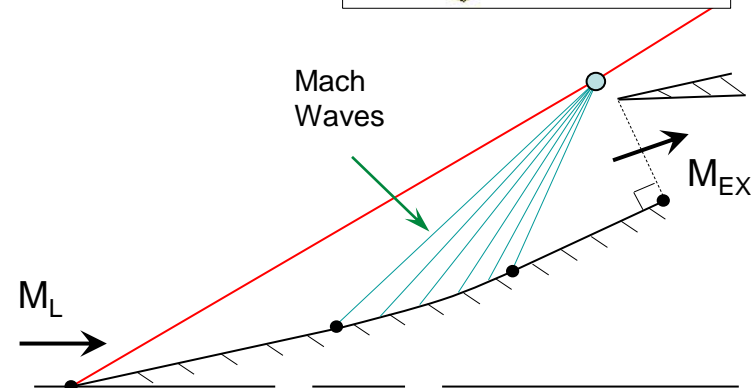


External Supersonic Diffuser

- An **External Supersonic Diffuser** is used for two-dimensional ($K_{typ} = 2$ or 4) and axisymmetric outward-turning ($K_{typ} = 3$) inlets.
- The **Nose** is the leading edge ($K_{typ} = 2$ or 4) or point ($K_{typ} = 3$) of the external supersonic diffuser. The nose can be sharp or round with a specified radius.
- The external supersonic diffuser consists of one or more **stages** through which compression occurs through each stage by means of an attached **shock wave** or isentropic **Mach waves**.
- Shock and Mach waves pass through **focal points** (e.g. shock-on-lip).
- Design strategies emphasize minimizing total pressure loss through the shocks and minimizing diffuser length while producing the desired outflow Mach number (M_{EX}).
- Two-dimensional diffusers include a sidewall to contain the compression.



Three-stage diffuser with shock waves



Three-stage diffuser with smooth turning

External Supersonic Diffuser Types

- The factor K_{exd} controls the number of stages and design methods.

$K_{exd} = 1$ & 2. Explicit specification of diffuser geometry using $\Delta\theta$, Δx , and Δy .

$K_{exd} = 3$. Explicit specification of diffuser geometry using lines, NURBS curves, polynomials, or cubic splines.

$K_{exd} = 10$. Single-stage ramp (2D) or cone (axi).

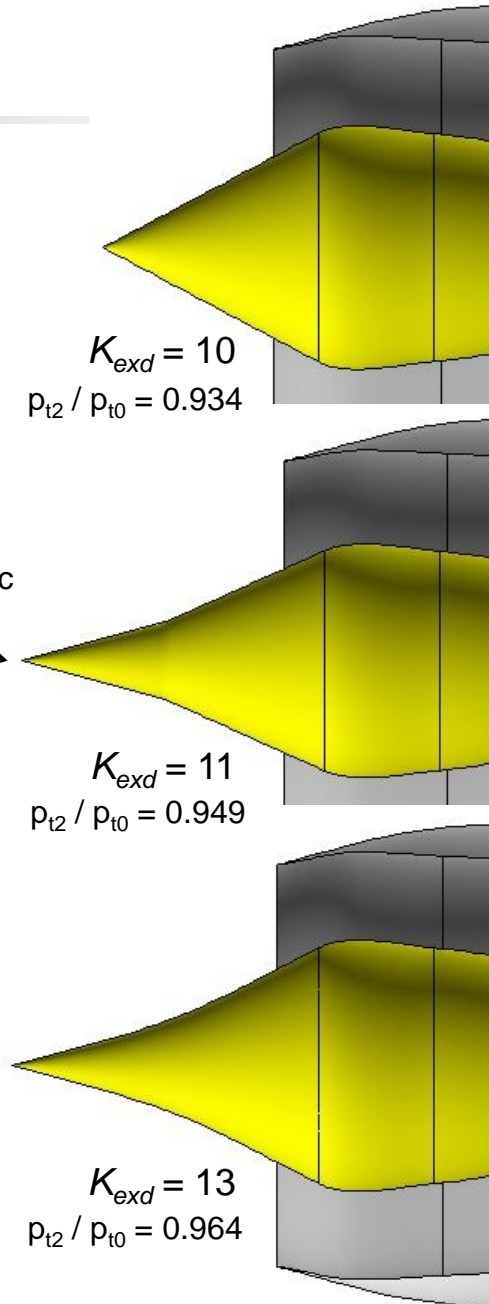
$K_{exd} = 11$. Two-stage ramp (2D) or bicone (axi).

$K_{exd} = 12$. Three-stage ramps (2D only).

$K_{exd} = 13$. Three-stages with second stage an isentropic compression surface.

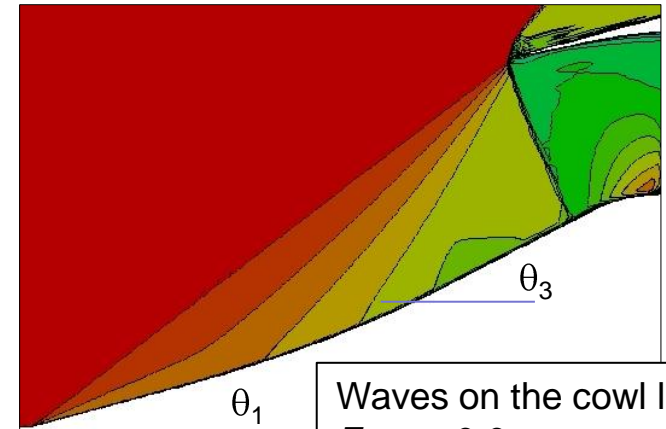
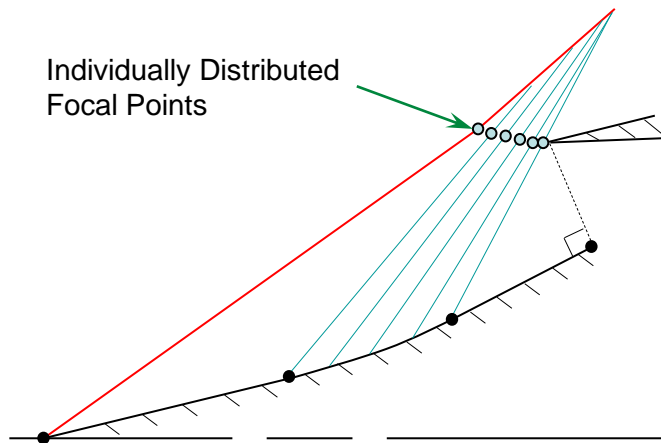
- For 2D ramps, a carpet search method is applied to determine the ramp angles that result in the maximum total pressure recovery for the diffuser (Oswatitsch condition).
- Conical flow solutions are determined using a numerical solution to the Taylor-Maccoll equations.
- Bi-conic flow and isentropic diffuser contours are determined using method-of-characteristics.
- Start and end of stages are determined by path of waves and placement of the focal points.

External
Supersonic
Diffuser

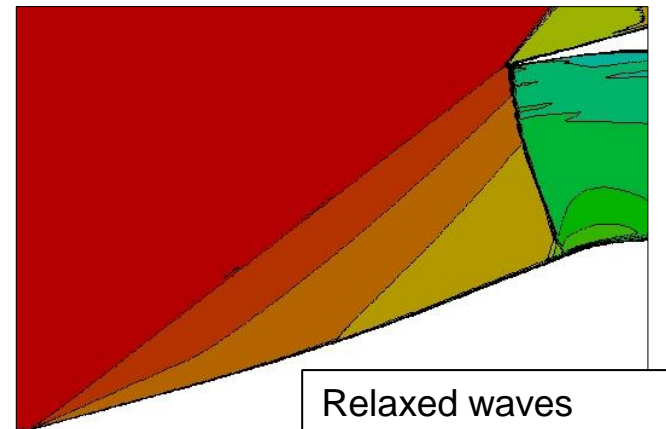


Relaxed External Compression

- Start and end of stages are determined by path of waves and placement of the focal points.
- May be desirable to alter focal points and wave angles to provide greater margins of stability or tailor the flow.
- Two ways of relaxing:
 1. Distribute the focal points for the waves.
 2. Relax the angle of a downstream stage using F_{relax} .
A value of $F_{relax} = 0$ would make downstream stage the same angle as upstream stage.



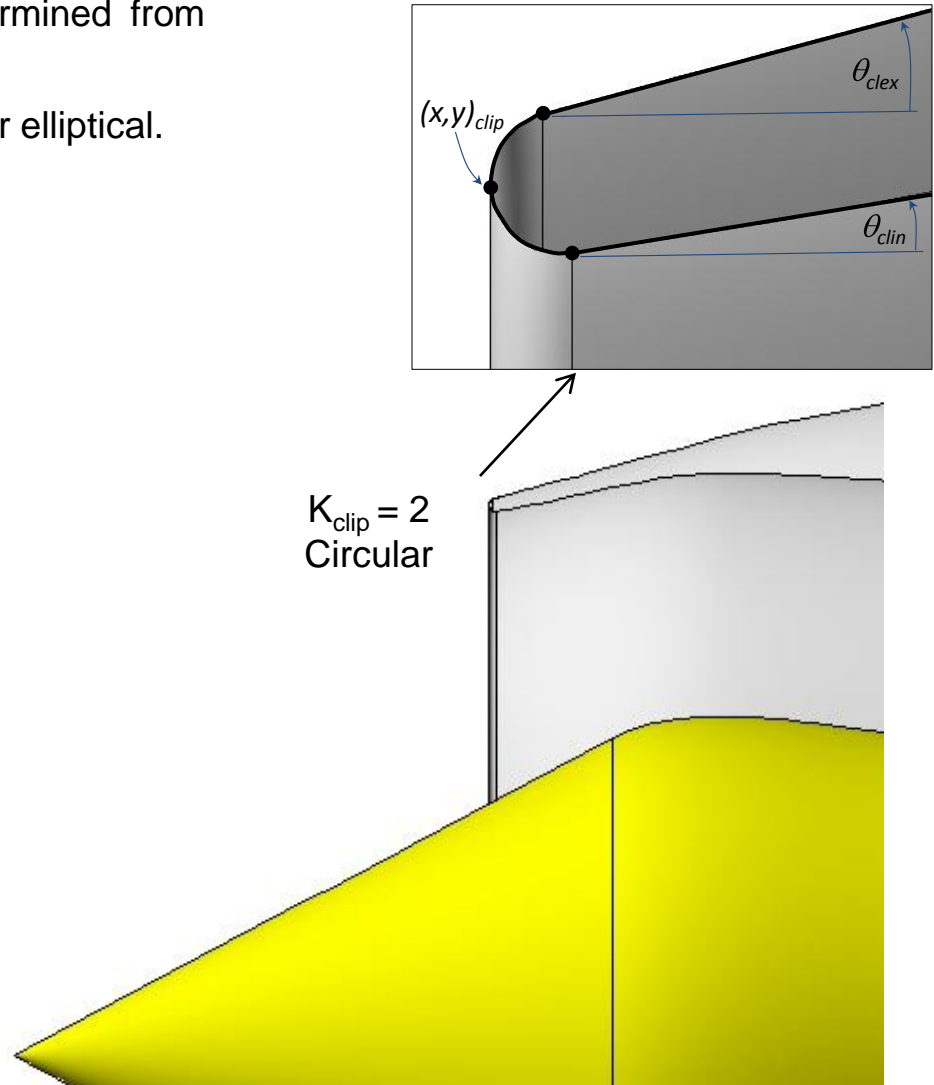
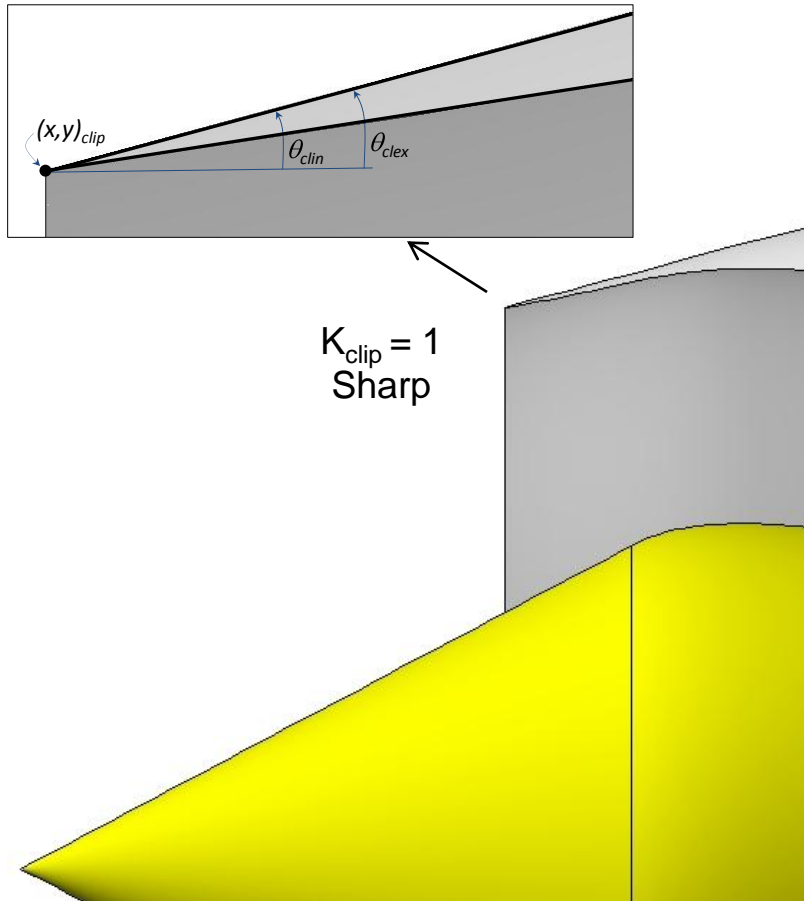
Waves on the cowl lip
 $F_{relax} = 0.0$
 $\theta_1 = 15^\circ$ $\theta_3 = 27.3^\circ$



Relaxed waves
 $F_{relax} = 0.5$
 $\theta_1 = 15^\circ$ $\theta_3 = 21.1^\circ$

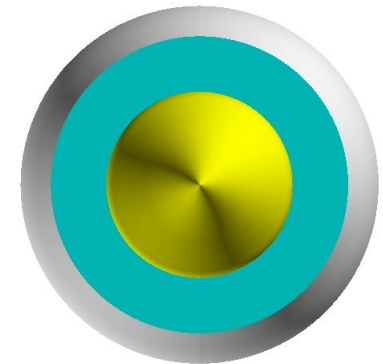
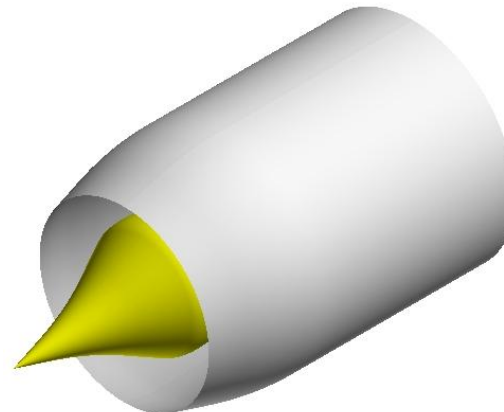
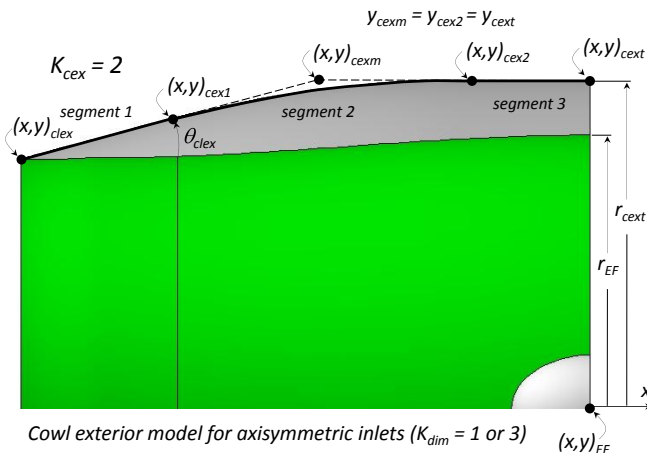
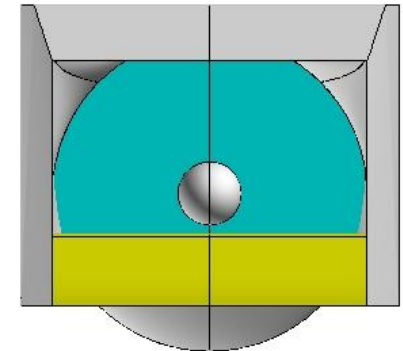
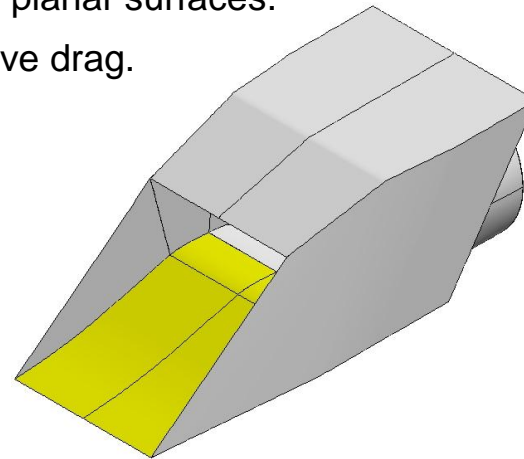
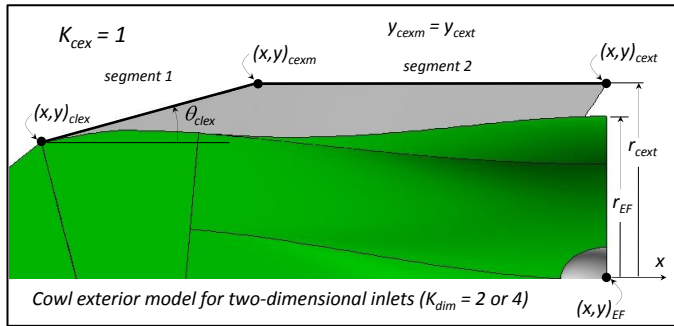
Cowl Lip

- Cowl Lip coordinate y_{clip} is specified or determined from sizing operations. The code sets $x_{clip} = 0$.
- Cowl Lip planar profile can be sharp, circular, or elliptical.



Cowl Exterior

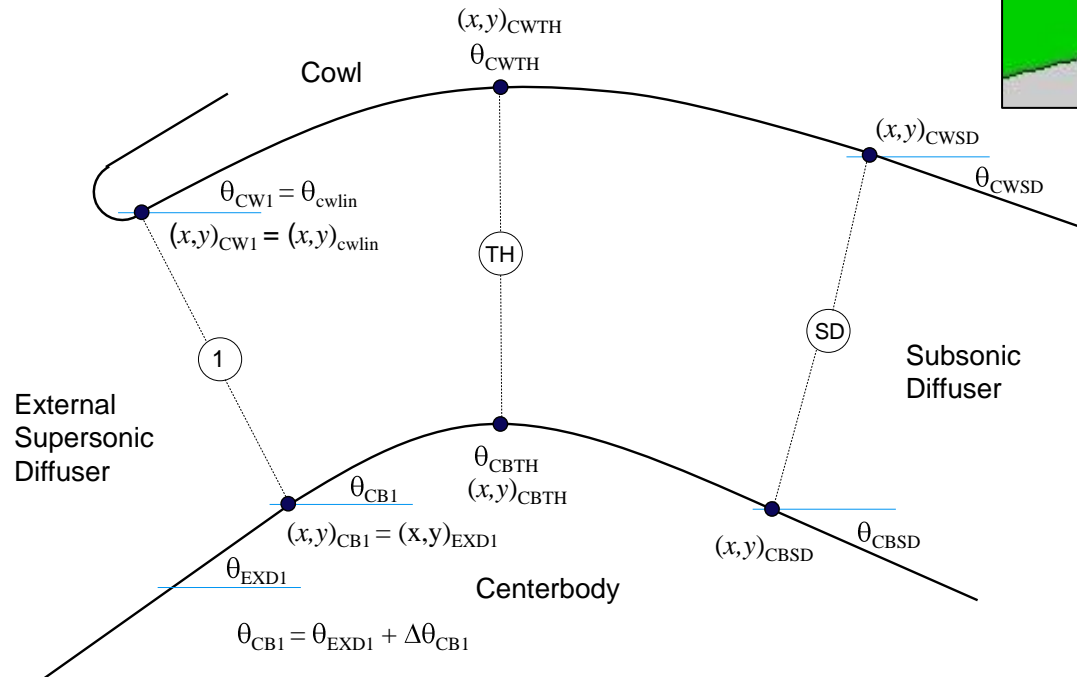
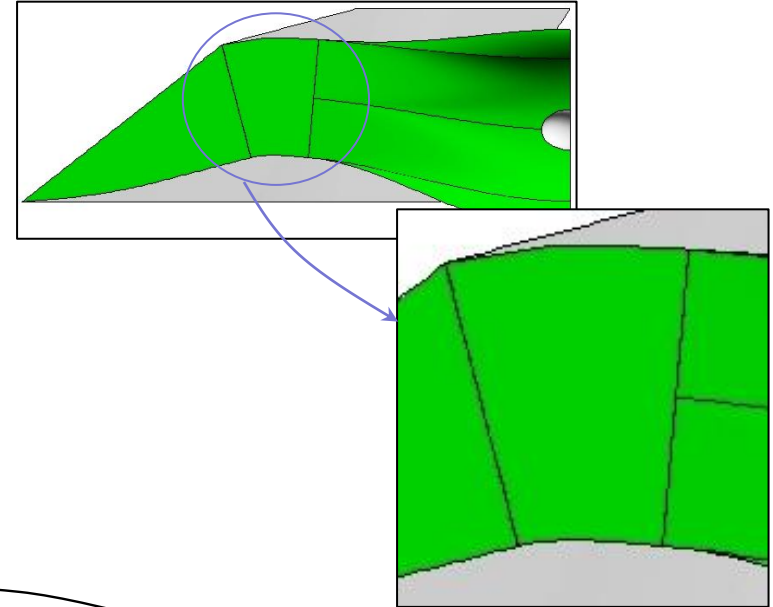
- Cowl Exterior provides an external surface for calculation of the wave drag.
- Geometry model creates baseline cowl exteriors based on factor F_{rcex} , which places the cowl exterior a multiple of the engine face radius.
- Axisymmetric cowl exteriors involve extruding a profile about the axis.
- Two-dimensional cowl exteriors involve building planar surfaces.
- Frontal area of cowl exterior influences cowl wave drag.



Throat

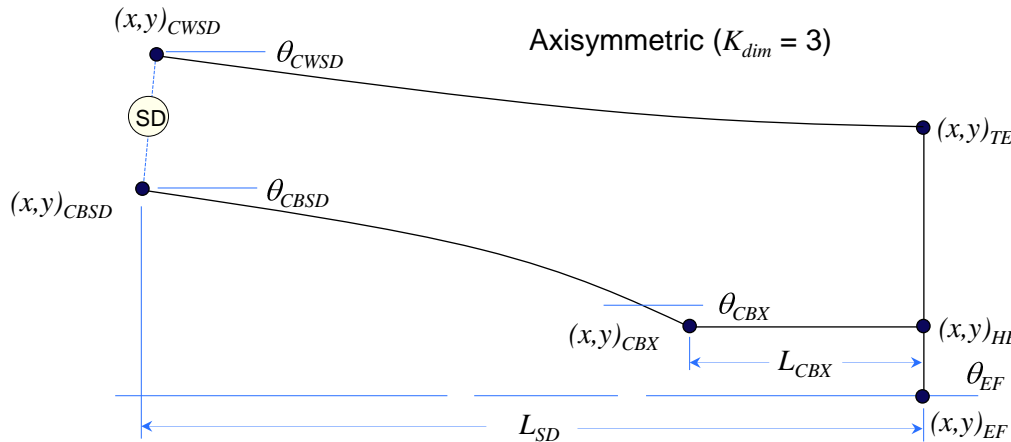
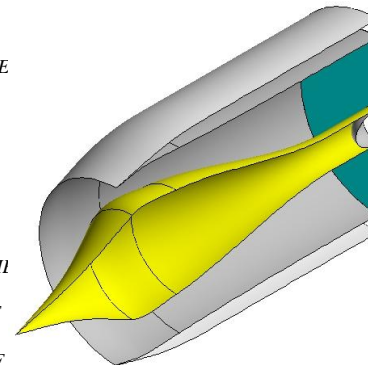
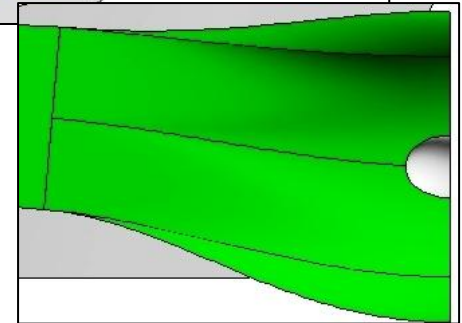
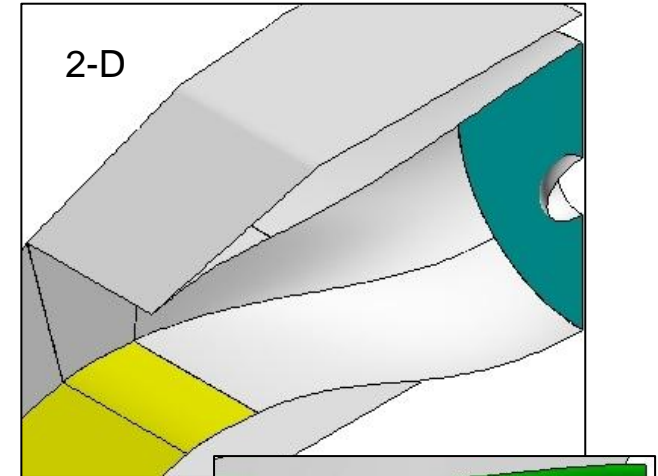


- Throat defines interior duct from stations 1 to SD.
- Station TH is the official “throat” station.
- The throat cross-sections follow the shape at station 1 (rectangular or axisymmetric).
- Throat area distribution is set by area ratios A_{TH} / A_1 and A_{SD} / A_{TH} .
- For $K_{thrt} = 2$, the area ratio is calculated such that Mach number M_{TH} is established at station TH.



Subsonic Diffuser

- The subsonic diffuser transitions from the cross-section at station SD to the cross-section at the engine face station 2.
- Two-dimensional inlets require transition from a rectangular to a circular. Surfaces are created by the blending of super-ellipses.
- Axisymmetric inlets are co-annular. Surfaces are created by extruding profiles about the axis-of-symmetry.
- Geometric factors include key surface angles.
- Length of subsonic diffuser can be directly specified or computed based on criteria of equivalent conical angle.



Inlet Flow Rates

- Quantify W_1 , W_2 , $W_{spillage}$, W_{bleed} , W_{bypass} , etc...
- We know some flow rate information for the engine (such as corrected flow, W_{C2}).
- Flow rates should satisfy continuity through the inlet streamtube.

$$\frac{W_2}{W_{cap}} = 1 - \frac{W_{spillage}}{W_{cap}} + \frac{W_{bleed}}{W_{cap}} + \frac{W_{bypass}}{W_{cap}} + \frac{W_{jets}}{W_{cap}} + \frac{W_{other}}{W_{cap}}$$

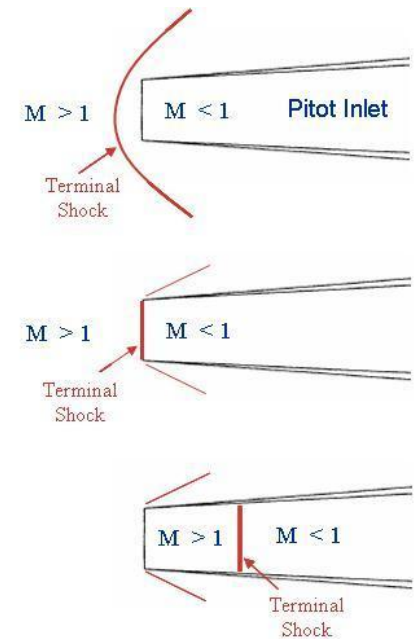
- W_{cap} is the theoretical capture flow rate.

- **Inlet Flow Ratio** = $\frac{W_1}{W_{cap}}$ (W_1 is the flow into the inlet)

- Three modes for external compression inlet flow rates in supersonic flow:
 - *Subcritical* (inlet flow ratio < 1, normal shock ahead of cowl lip)
 - *Critical* (inlet flow ratio = 1, normal shock at the cowl lip)
 - *Supercritical* (inlet flow ratio = 1, normal shock within the internal duct)

- Spillage is defined as $\frac{W_{spillage}}{W_{cap}} = 1 - \frac{W_1}{W_{cap}}$

- **Engine Flow Ratio** = $\frac{W_2}{W_{cap}}$



IPAC Manual. Fig. 3.

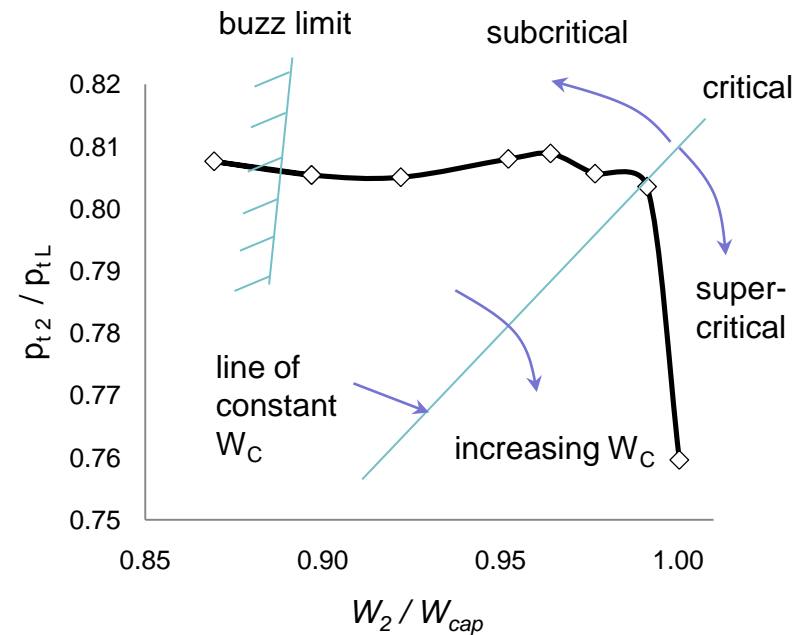


Inlet Total Pressure Recovery

- Inlet Total Pressure Recovery = $\frac{P_{t2}}{P_{tL}}$
- Recovery is computed as increments through the inlet,

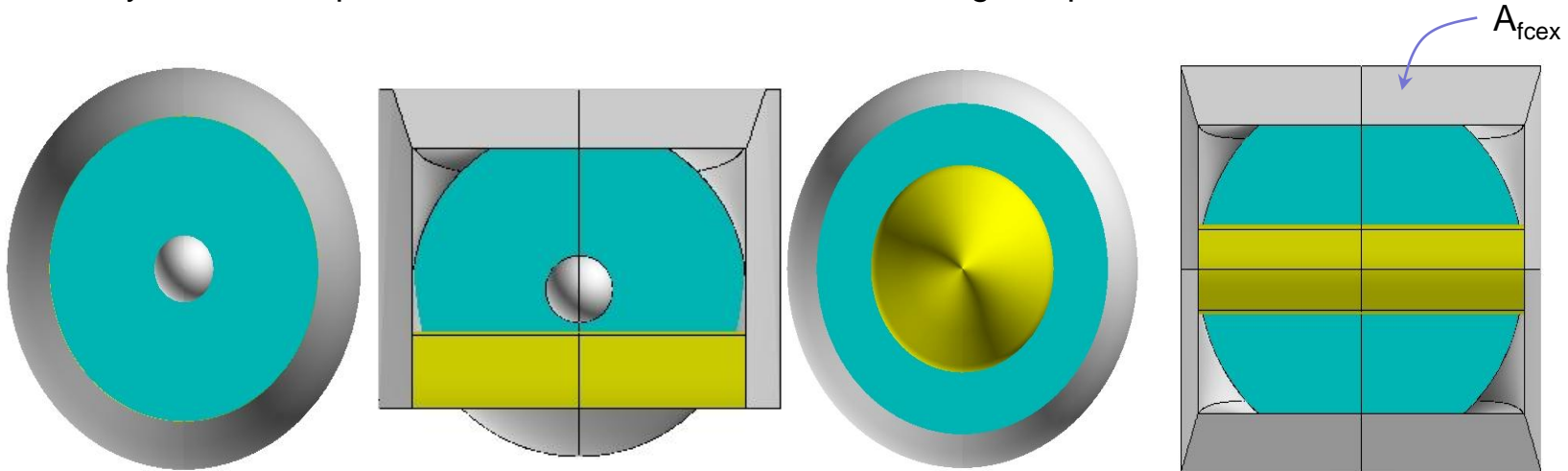
$$\frac{P_{t2}}{P_{tL}} = \frac{P_{tEX}}{P_{tL}} \frac{P_{tNS}}{P_{tEX}} \frac{P_{t1}}{P_{tNS}} \frac{P_{tTH}}{P_{t1}} \frac{P_{tSD}}{P_{tTH}} \frac{P_{t2}}{P_{tSD}}$$

- Total pressure losses modeled within SUPIN:
 - Normal, oblique, and conical shock waves
 - Viscous diffusion supersonically or subsonically
 - Sharp lip losses at high inlet flow rates at low speeds (high inlet flow ratio)
- Inlet design objective is to maximize the total pressure recovery.
- Characteristic cane curve relates the total pressure recovery to the inlet flow ratio or engine flow ratio.



Inlet Drag

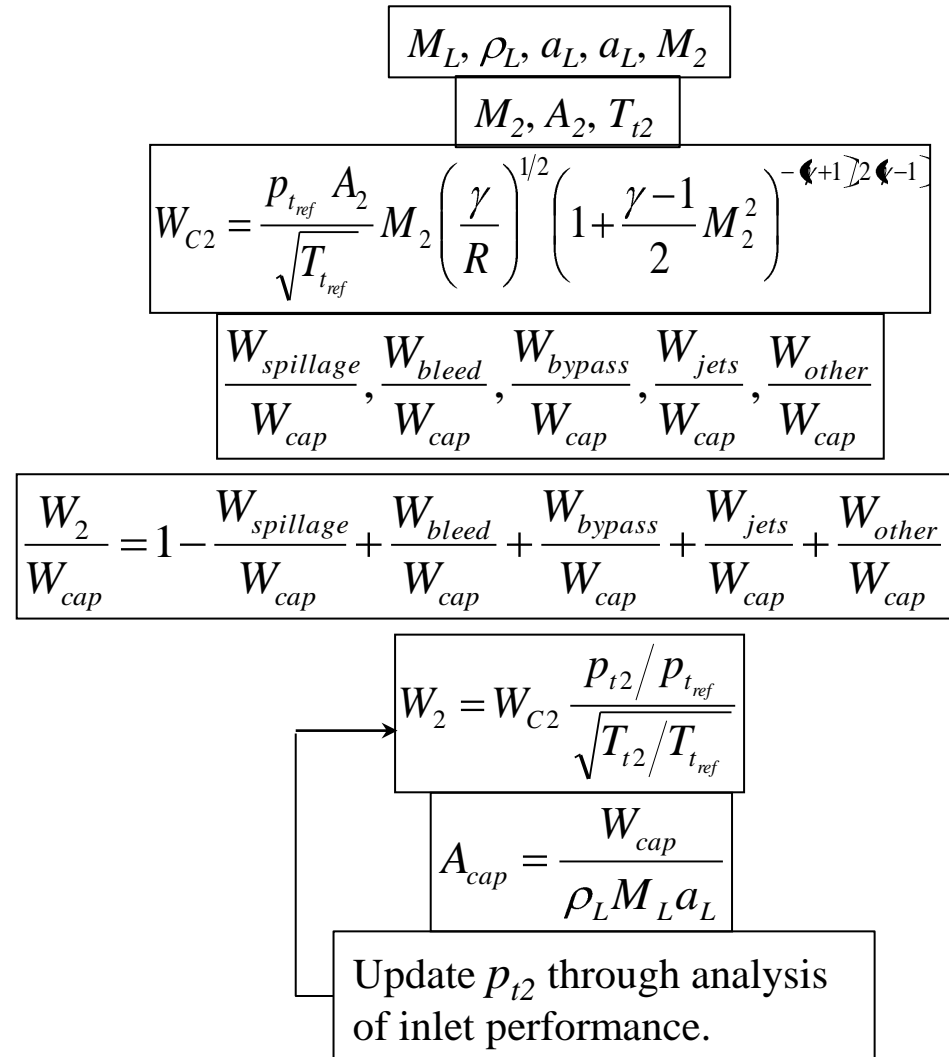
- Inlet drag consists of those drag components that can vary with inlet flow rate.
- Inlet drag components:
 - Spillage Drag (Additive drag + Cowl lip suction)
 - Cowl Drag (Cowl lip drag + Wave drag)
 - Bleed and bypass drag
- Additive drag is the sum of axial pressure forces acting on the streamtube ahead of the cowl lip.
- Cowl lip suction accounts for positive force due to acceleration of flow around a blunt cowl lip.
- Wave drag is the sum of axial pressure forces on the cowl exterior caused by supersonic flow.
- Bleed and bypass drag are the result of the loss of momentum of airflow through bleed and bypass systems.
- Analytical and empirical methods are used to estimate drag components.





Inlet Sizing

- Inlet sizing establishes the inlet dimensions (A_{cap} , L_{SD} , L_{exd} , A_1 , A_{TH} , A_{SD} , angles, etc...)
- Sizing enforces the flow rate balance through the inlet, and so, establishes the actual flow rates (W_1 , W_2).
- Sizing uses the total pressure recovery, which is dependent on the sizing of the inlet. Thus an iteration is involved that starts with an estimate of the recovery that is improved with successive iterations.
- Within SUPIN, the iteration is performed by successive executions of SUPIN. With each iteration, the input data file is updated with the geometry properties and the total pressure recovery.

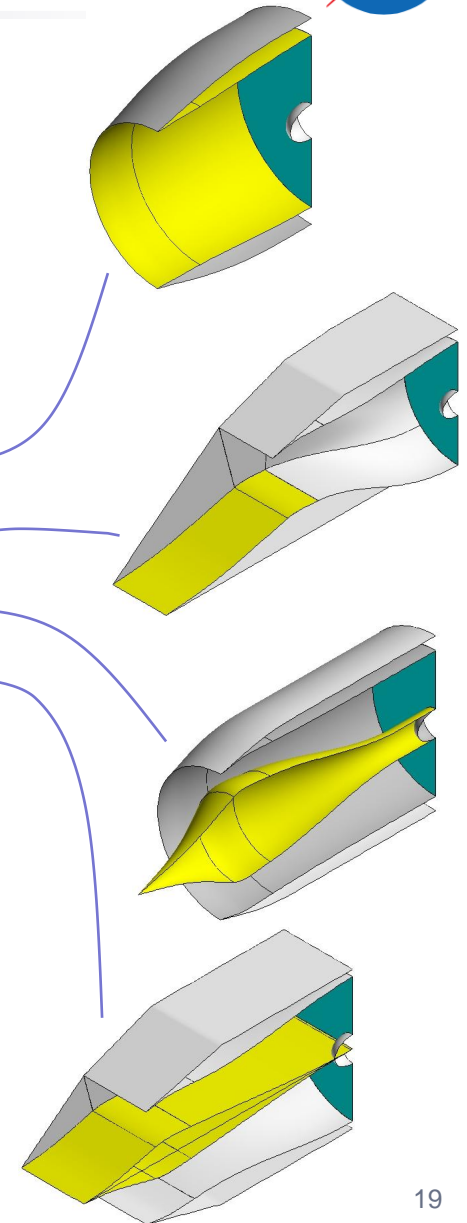


Inlet Design Study

- Apply SUPIN to design a set of baseline inlets.
- $M_0 = 1.8$, $h_{alt} = 45000$ ft., $M_2 = 0.5$, $D_2 = 3.5$ ft.
- Sharp nose. Three stages for the external supersonic diffuser ($K_{exd} = 13$). $M_{EX} = 1.3$. Shock-on-lip. Sharp cowl lip. Equivalent conical angle for the subsonic diffuser = 3° .

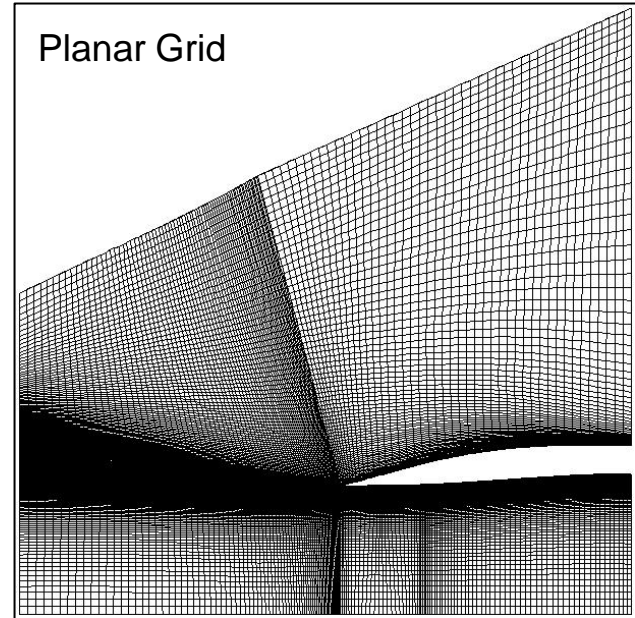
Inlet	W_2 (slug/s)	p_{t2}/p_{t0}	h_{clip} (ft)	L (ft)	A_{cap} (ft ²)	A_{fcex} (ft ²)	C_{Dwave}
Pitot	6.4330	0.8088	3.196	3.626	8.023	5.832	0.3313
2D	7.6450	0.9611	2.724	9.545	2.191	0.0947	
Axisym	7.6665	0.9638	3.489	8.240	9.561	4.293	0.2233
Bifurcated	7.6455	0.9612	2.724	7.507	9.535	3.940	0.0852

- Conclusions:
 - Pitot inlet does not perform well.
 - Flow rate (W_2) increases with higher total pressure recovery, but essentially the same between 2D and axisymmetric external compression.
 - Total pressure recovery is the same between 2D and axisymmetric external compression.
 - Two-dimensional bifurcated inlet is shortest inlet.
 - Cowl external wave drag is significantly less for two-dimensional inlets.



CFD Analyses

- SUPIN can create planar, structured, multi-block grid for 2D or axisymmetric CFD.
- Use CFD methods (Wind-US) to solve planar flow field.
- Compute performance measures as a verification for SUPIN.
- 3D surface grids can be start to 3D grid generation.

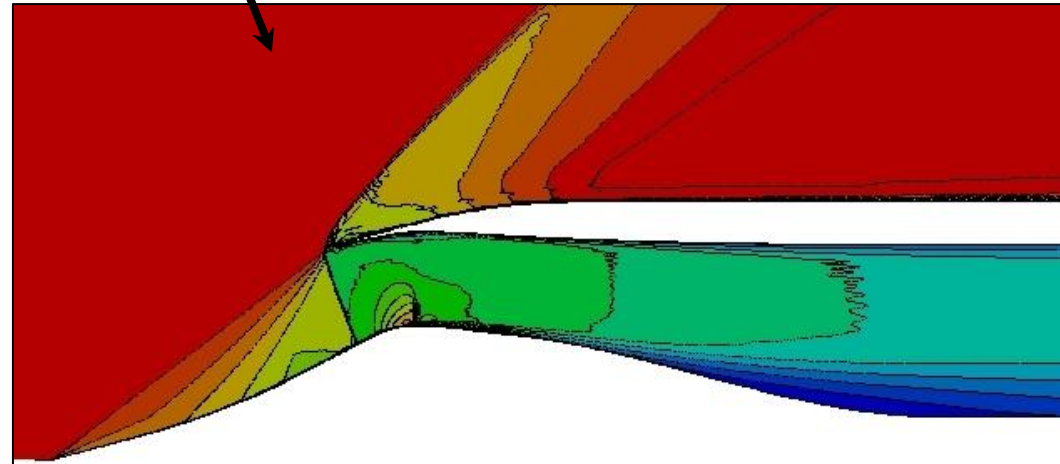
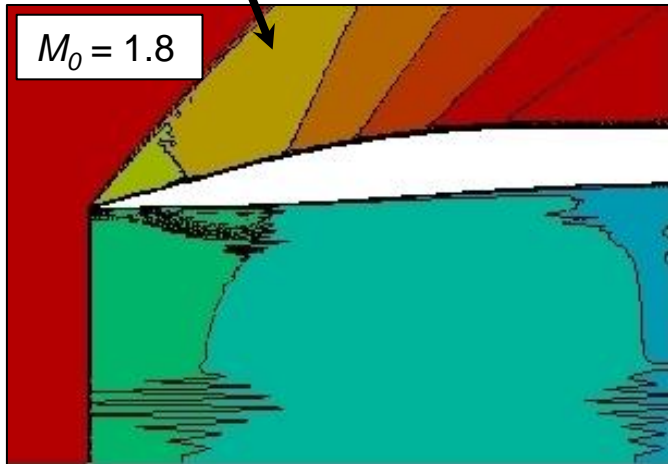


Axisymmetric, Pitot Inlet ($K_{typ} = 1$)

Method	W_2 (slug/s)	p_{t2}/p_{t0}	C_{Dwave}
SUPIN	6.4330	0.8088	0.3313
CFD	6.4039	0.8094	0.2764
Diff	0.45%	-0.08%	16.55%

Axisymmetric, O-T Inlet ($K_{typ} = 3$)

Method	W_2 (slug/s)	p_{t2}/p_{t0}	C_{Dwave}
SUPIN	7.6665	0.9638	0.2233
CFD	7.2946	0.9317	0.1706
Diff	4.85%	3.34%	23.58%



Future Plans

- Initial releases (March 2011):
 - SUPIN as a beta test code
 - Inlet Tools eRoom
 - Inlet Design and Analysis Document (*review draft*)
- Continue the development of SUPIN:
 - Enhance off-design performance analysis capability ($K_{mode} = 3$).
 - Develop capability for design and analysis of internal and mixed-compression inlets.
 - Incorporate variable-geometry elements.
 - Develop capability for design and analysis of three-dimensional or stream-traced inlets.
 - Incorporate quasi-one-dimensional CFD methods.
- Explore other programming options and platforms (Java).
- Explore partnerships with other researchers and organizations to document and develop inlet tools.
- Contact: John.Slater@nasa.gov (216) 433-8513

