Coupled Analysis of an Inlet and Fan for a Quiet Supersonic Aircraft

by

Rodrick V. Chima
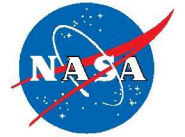NASA Glenn Research Center, Cleveland, OH
and
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Gulfstream Aerospace Corporation, Savannah, GA

A computational analysis of a Gulfstream isentropic external compression supersonic inlet coupled to a Rolls-Royce fan was completed. The inlet was designed for a small, low sonic boom supersonic vehicle with a design cruise condition of $M = 1.6$ at 45,000 feet. The inlet design included an annular bypass duct that routed flow subsonically around an engine-mounted gearbox and diverted flow with high shock losses away from the fan tip. Two Reynolds-averaged Navier-Stokes codes were used for the analysis: an axisymmetric code called AVCS for the inlet and a 3-D code called SWIFT for the fan. The codes were coupled at a mixing plane boundary using a separate code for data exchange. The codes were used to determine the performance of the inlet / fan system at the design point and to predict the performance and operability of the system over the flight profile. At the design point the core inlet had a recovery of 96 percent, and the fan operated near its peak efficiency and pressure ratio. A large hub radial distortion generated in the inlet was not eliminated by the fan and could pose a challenge for subsequent booster stages. The system operated stably at all points along the flight profile. Reduced stall margin was seen at low altitude and Mach number where flow separated on the interior lips of the cowl and bypass ducts. The coupled analysis gave consistent solutions at all points on the flight profile that would be difficult or impossible to predict by analysis of isolated components.
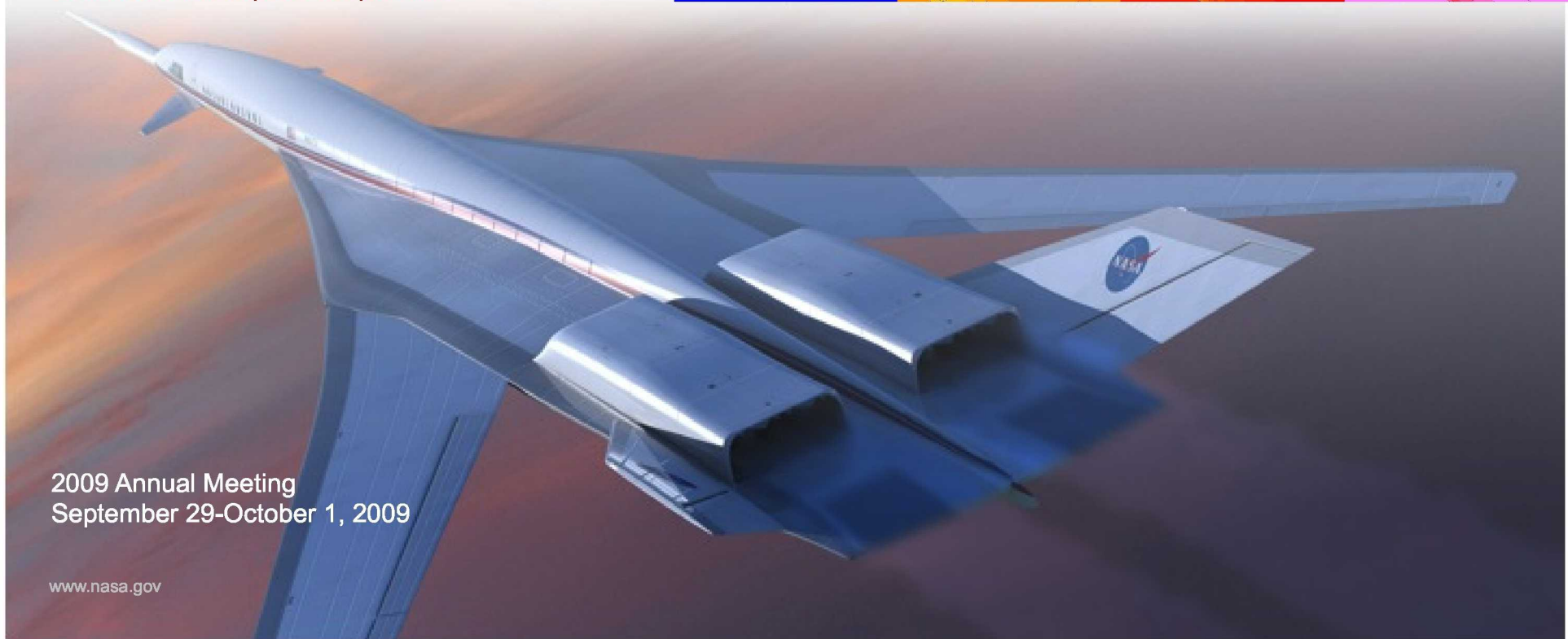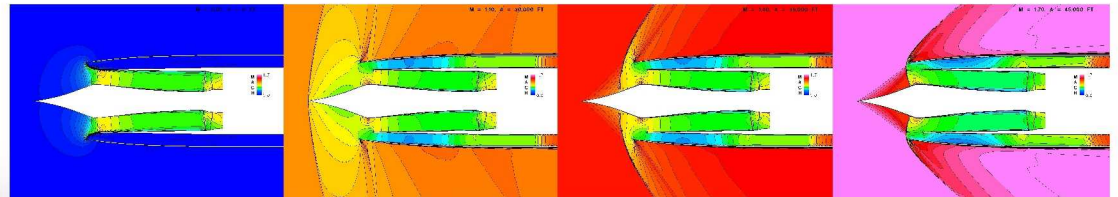
Coupled Analysis of an Inlet and Fan for a Quiet Supersonic Aircraft

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2009 Annual Meeting
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Objectives

1. Develop CFD tools for coupled inlet / fan interaction.

2. Apply the tools to a Gulfstream supersonic inlet coupled to the fan for a Rolls-Royce engine.

3. Determine the performance of the system at the design point.

4. Assess the operability of the system over the flight profile.

AVCS code

Axisymmetric Navier-Stokes duct analysis code by D. Tweedt and R. Chima
  - Node centered finite-difference formulation
  - AUSM[+] upwind differencing
  - Axisymmetric blockage term used to model gearbox blockage

Explicit Runge-Kutta solver
  - Variable Δt
  - Implicit residual smoothing

Turbulence model
  - Wilcox 2006 k-ω turbulence model and stress limiter

SWIFT code

3-D multiblock Navier-Stokes turbomachinery analysis code by R. Chima
- Node centered finite-difference formulation
- AUSM$^+$ upwind differencing

Explicit Runge-Kutta solver
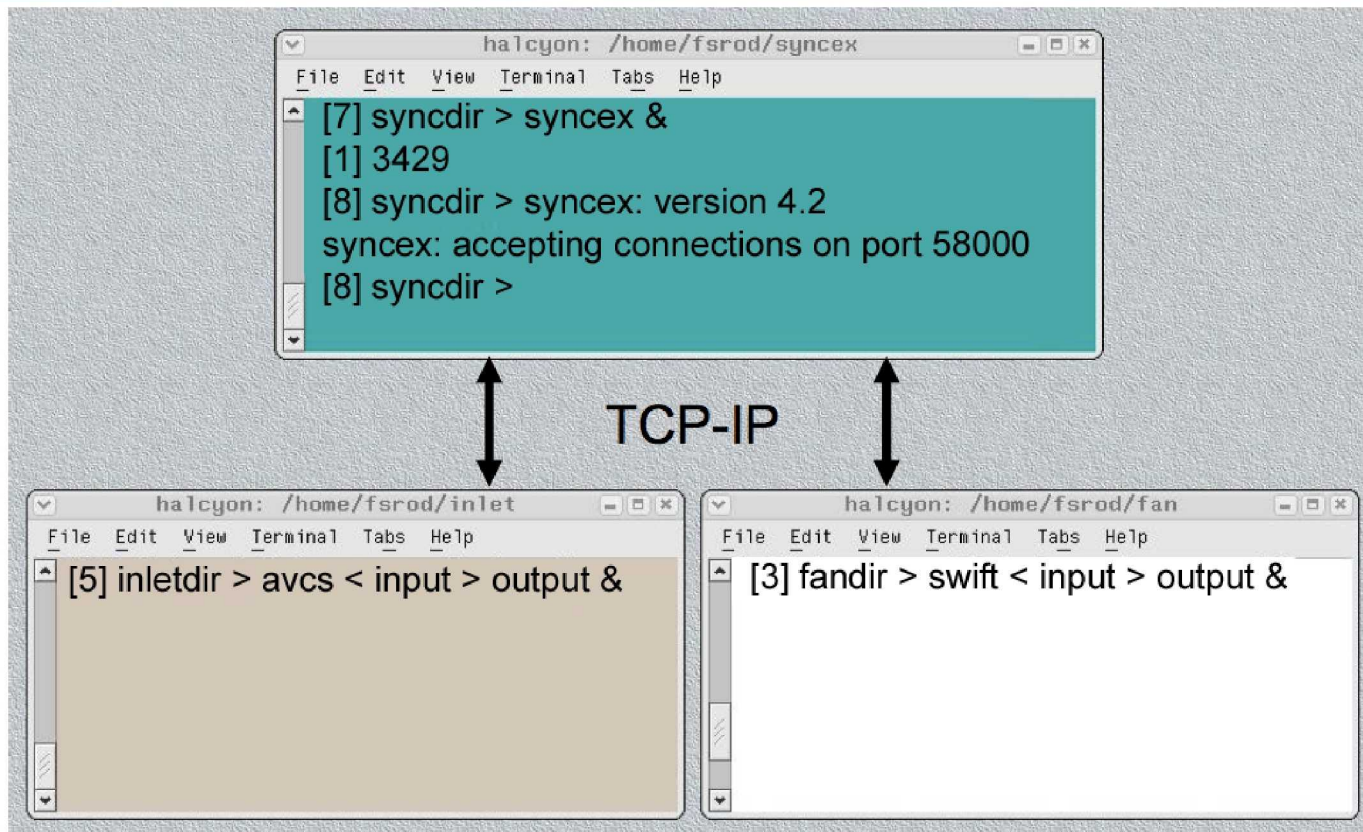- Variable Δt
- Implicit residual smoothing

Turbulence model
- Wilcox 2006 k-ω turbulence model with stress limiter

Coupled to AVCS with a steady mixing plane model
- SWIFT blade-to-blade solution perturbed about AVCS solution using Giles' characteristic BC

Code Coupling - SYNCEX

SYNCEX – C language code written by Dr. Dan Tweedt of AP Solutions, Inc.
- Runs in the background and handles data communication, storage, and synchronization between CFD codes
- User routines read and write boundary condition data to SYNCEX
- General interpolation routines provided

Application - Gulfstream Quiet Supersonic Jet

- Conceptual design by Gulfstream Aerospace Corporation (GAC)
- Mach 1.6 cruise at 45,000 ft
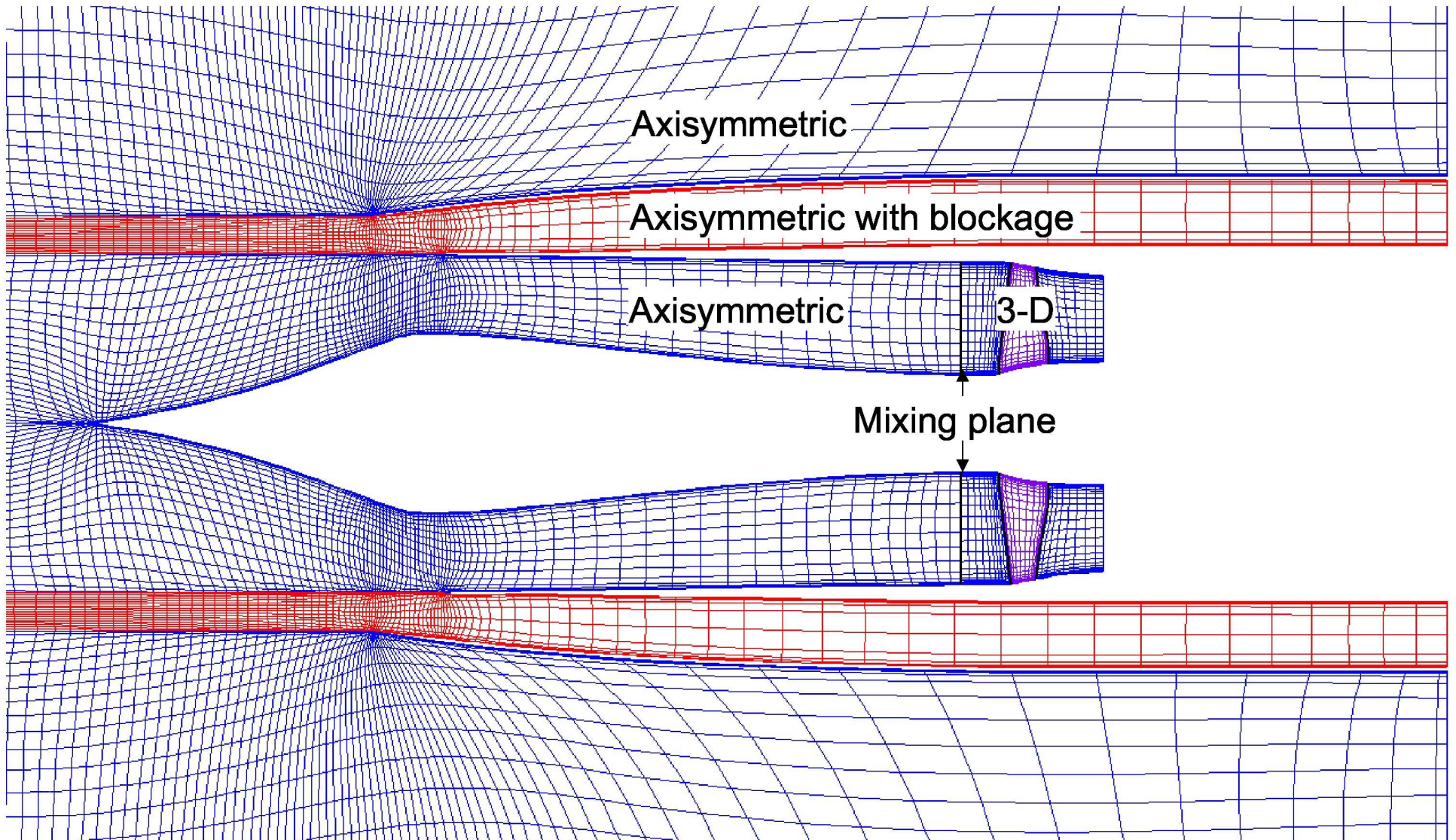- Extensive shaping to minimize sonic boom for flight over land

Gulfstream Inlet / Rolls-Royce fan

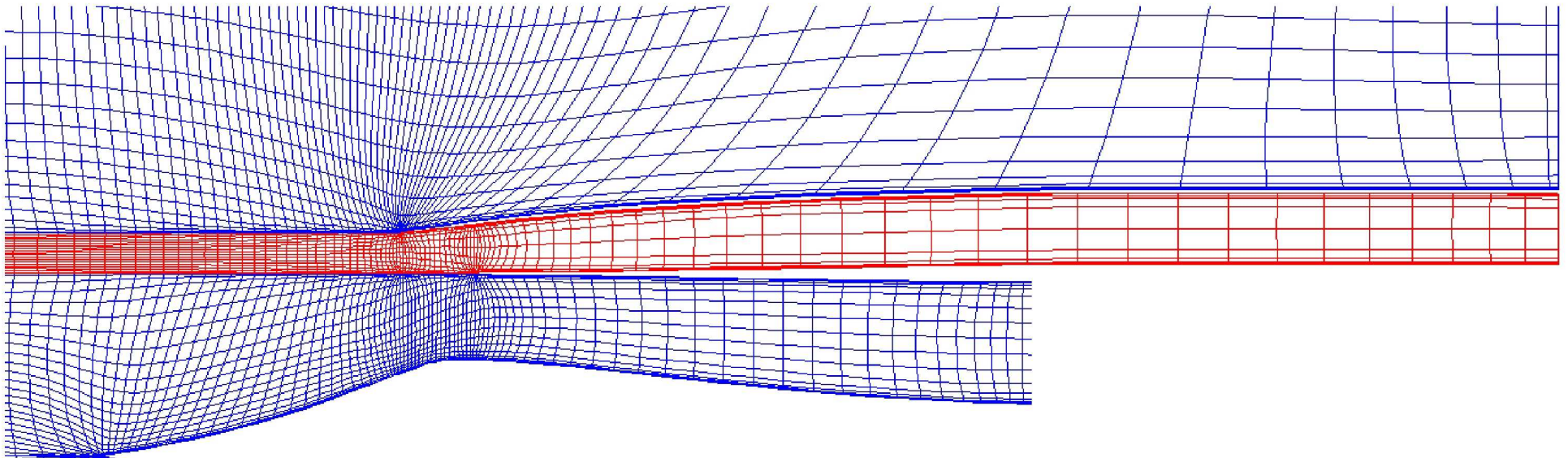Mach 1.7 External Compression Inlet   Rolls-Royce Engine   Nozzle
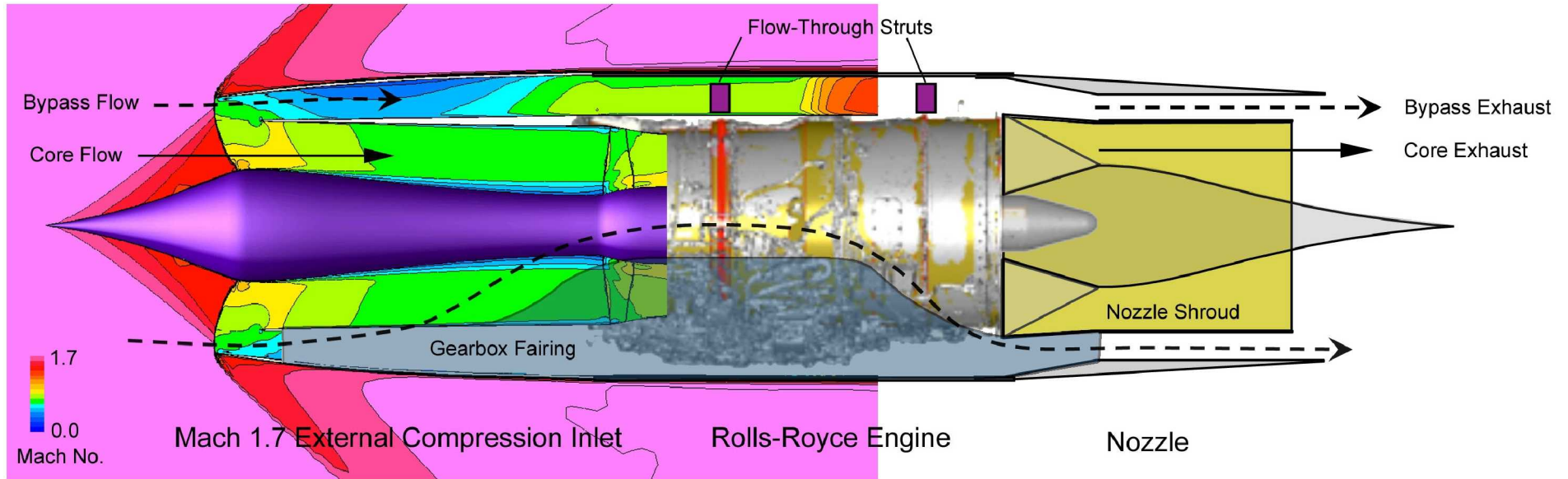
- Isentropic external compression inlet
- Rolls-Royce engine
- Plug nozzle
- Novel bypass duct routes flow internally around large gearbox

Computational grids
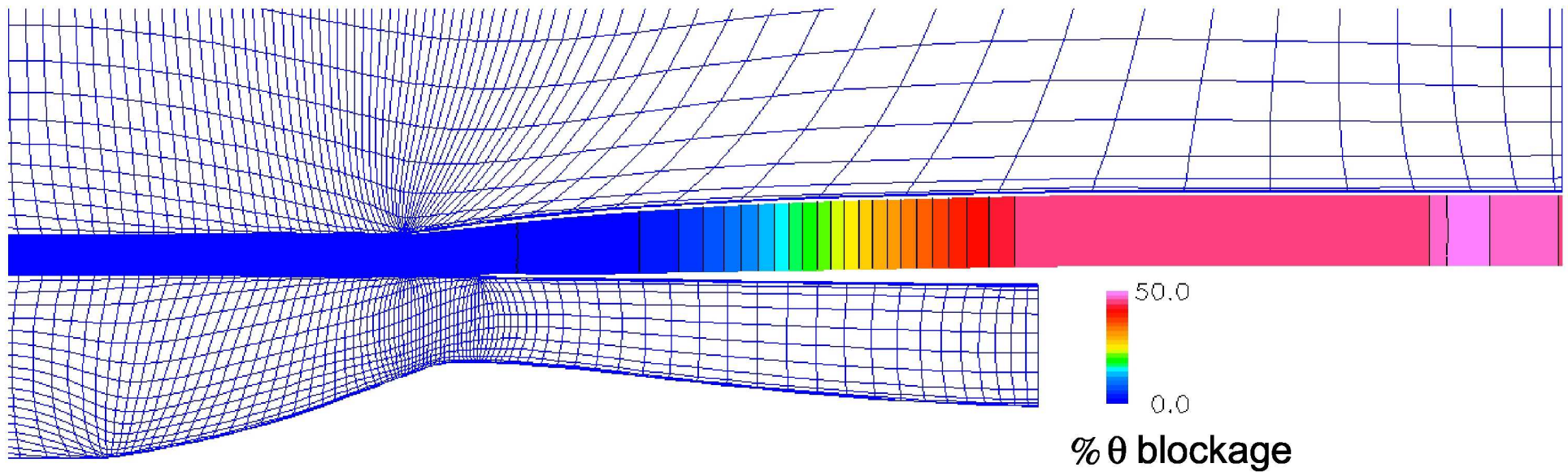
Axisymmetric inlet / bypass grid

SIGG grid code by D. Tweedt
- Algebraic grid with elliptic smoother used for inlet, bypass, and external flow
- $y^+ = 1 - 2.5$

Region	Type	Size (x, r)	Total points
inlet	H	419 x 95	39,805
bypass	H	439 x 55	24,145
external flow	H	360 x 128	46,080
Total			110,030

Gearbox fairing blockage

%θ blockage

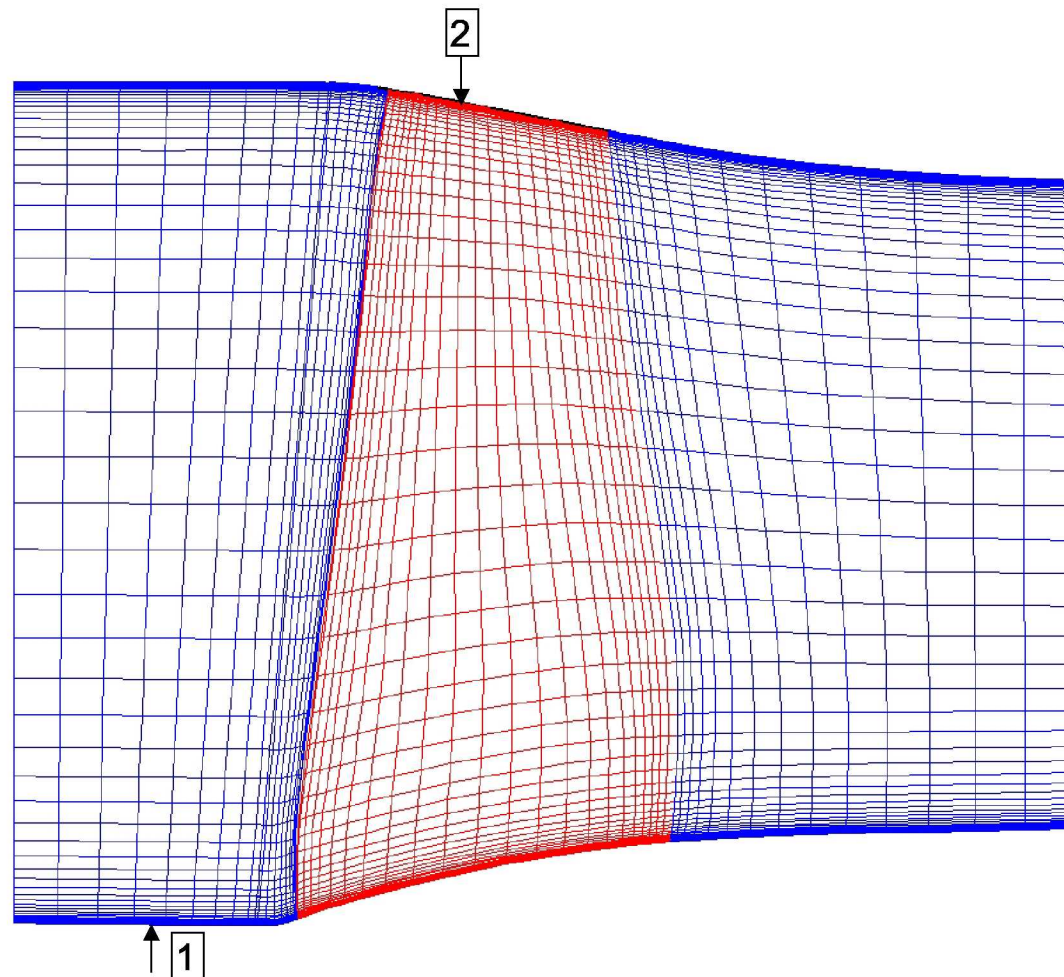- Gearbox fairing modeled using specified blockage in bypass duct grid

3-D fan grid

TCGRID grid code by R. Chima

- Algebraic H-grid upstream
- Elliptic C-grids around blades
- Algebraic O-grids in tip clearance region
- $y^+ = 1 - 2.5$

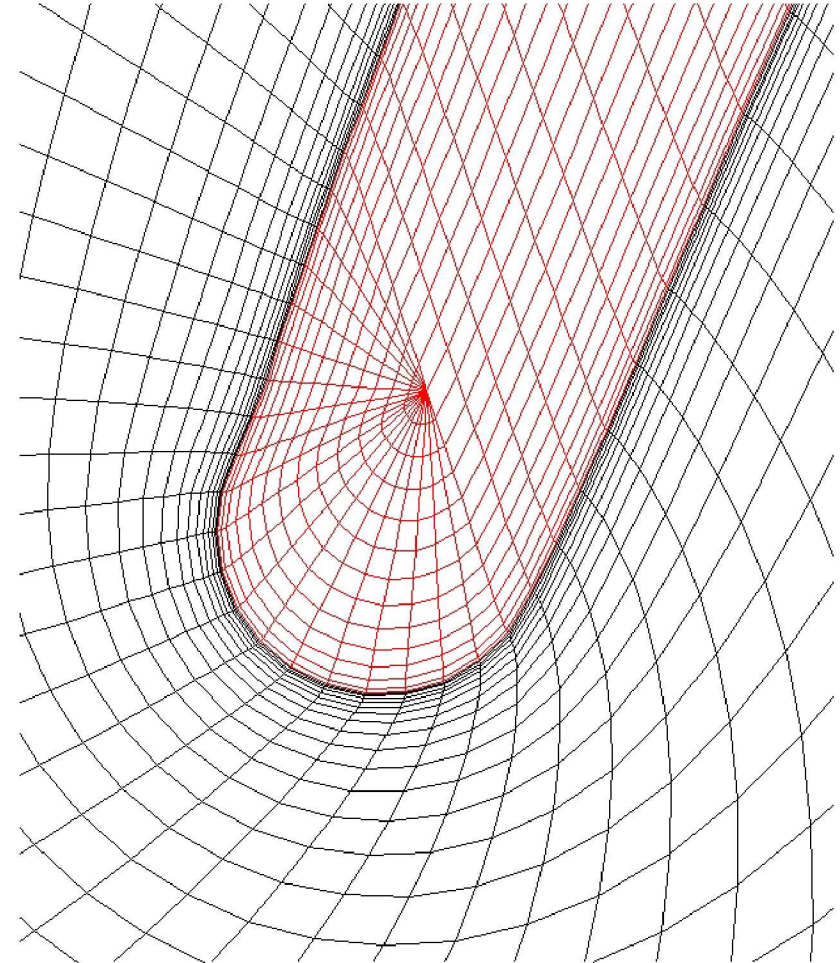| Region	Type	Size (x, q, r)	Total points
upstream	H	45 x 30 x 95	128,250
rotor	C	257 x 46 x 95	1,123,090
rotor tip	O	201 x 15 x 15	45,225
Total			1,296,565
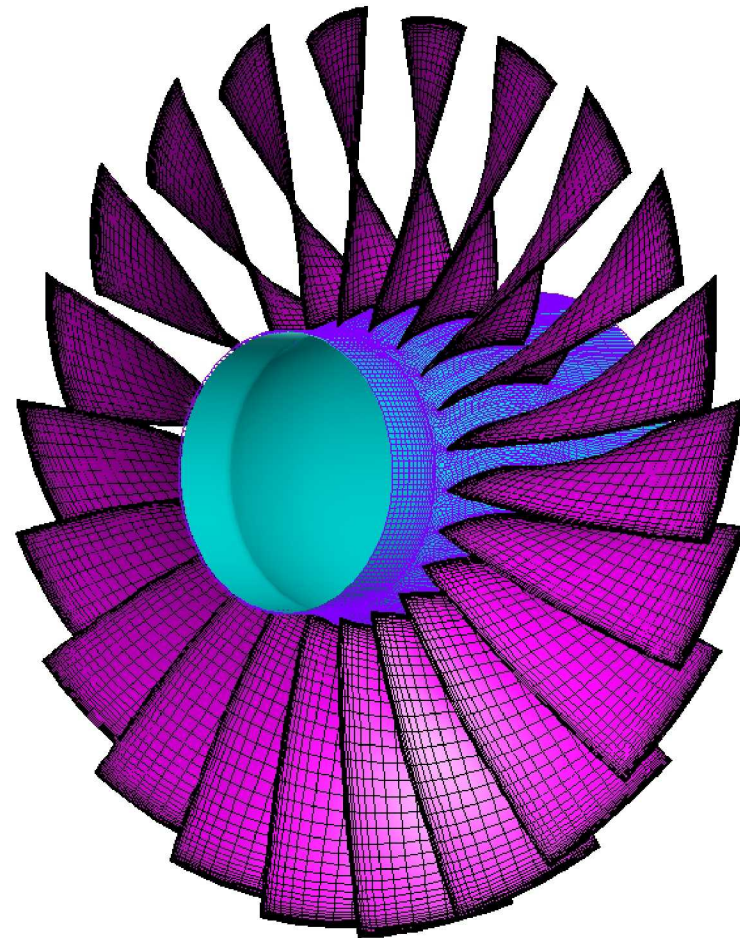
Grid details

1. Inlet centerbody radius matched to rotor hub.
2. Tip clearance is unknown. Used 0.025 inches.
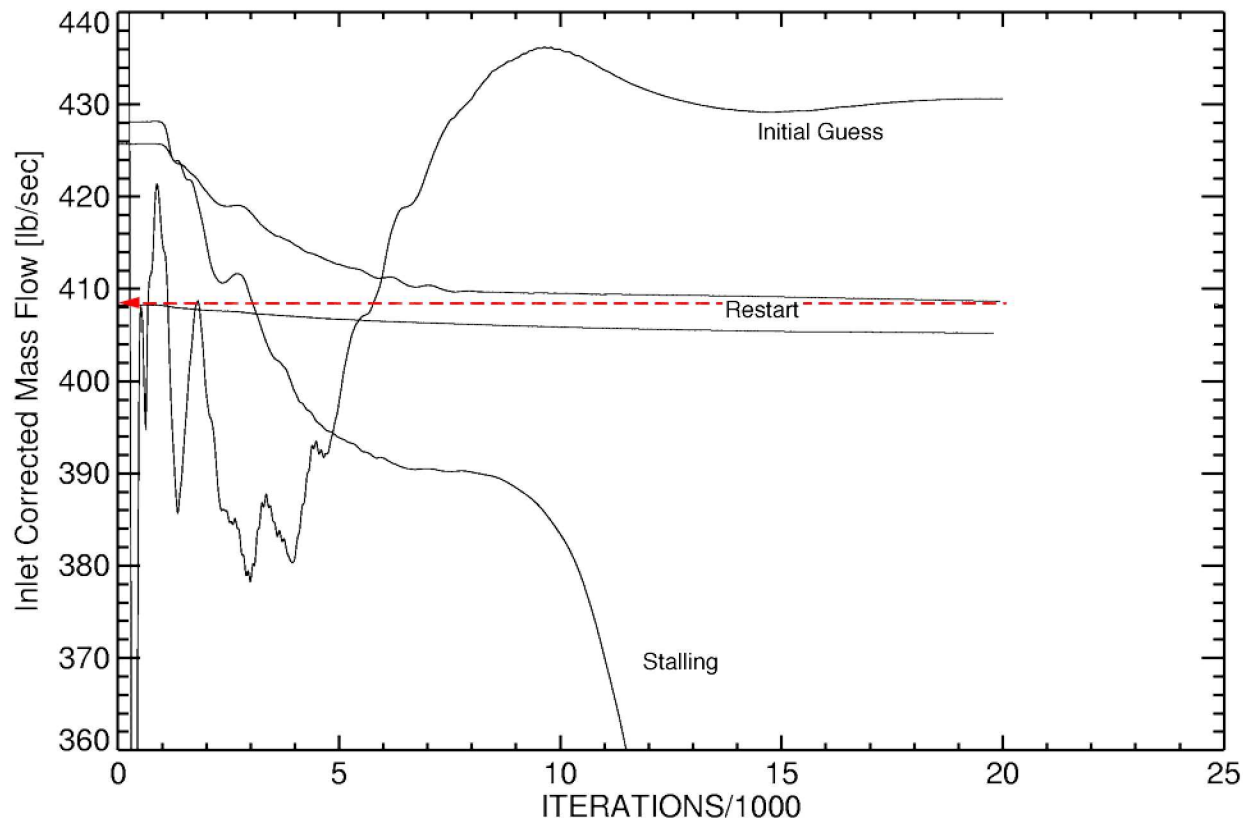
Grid details
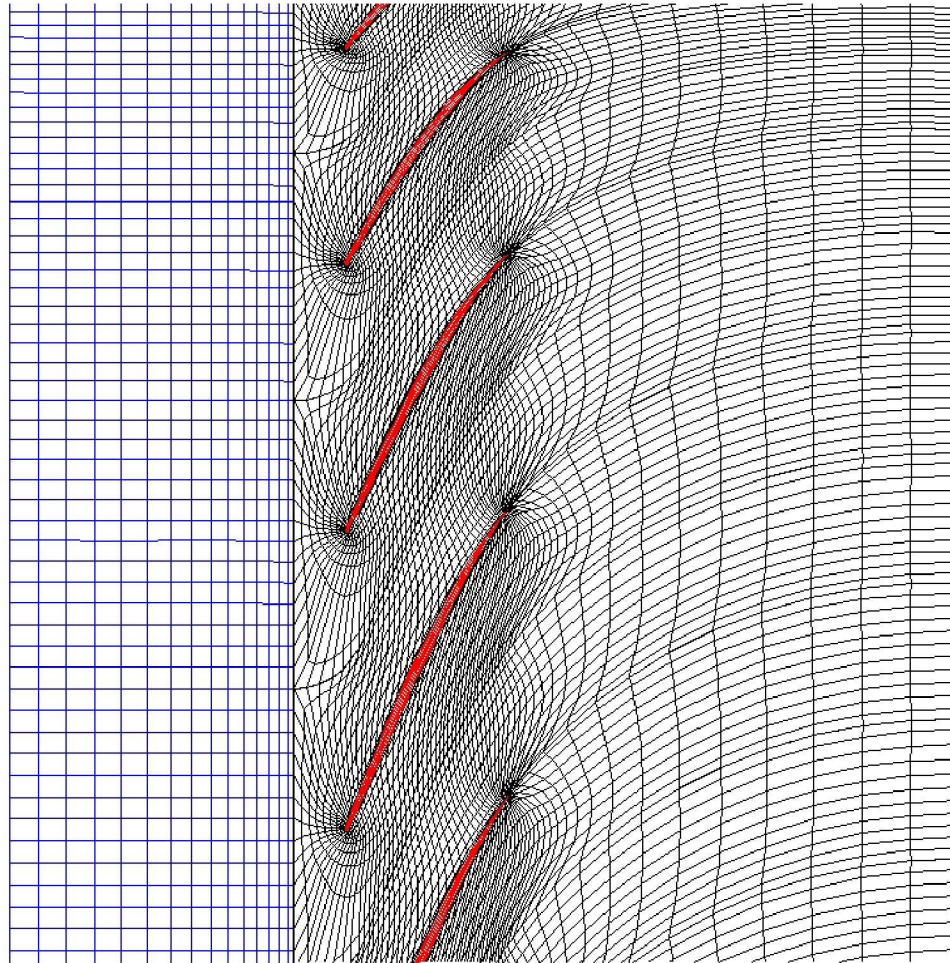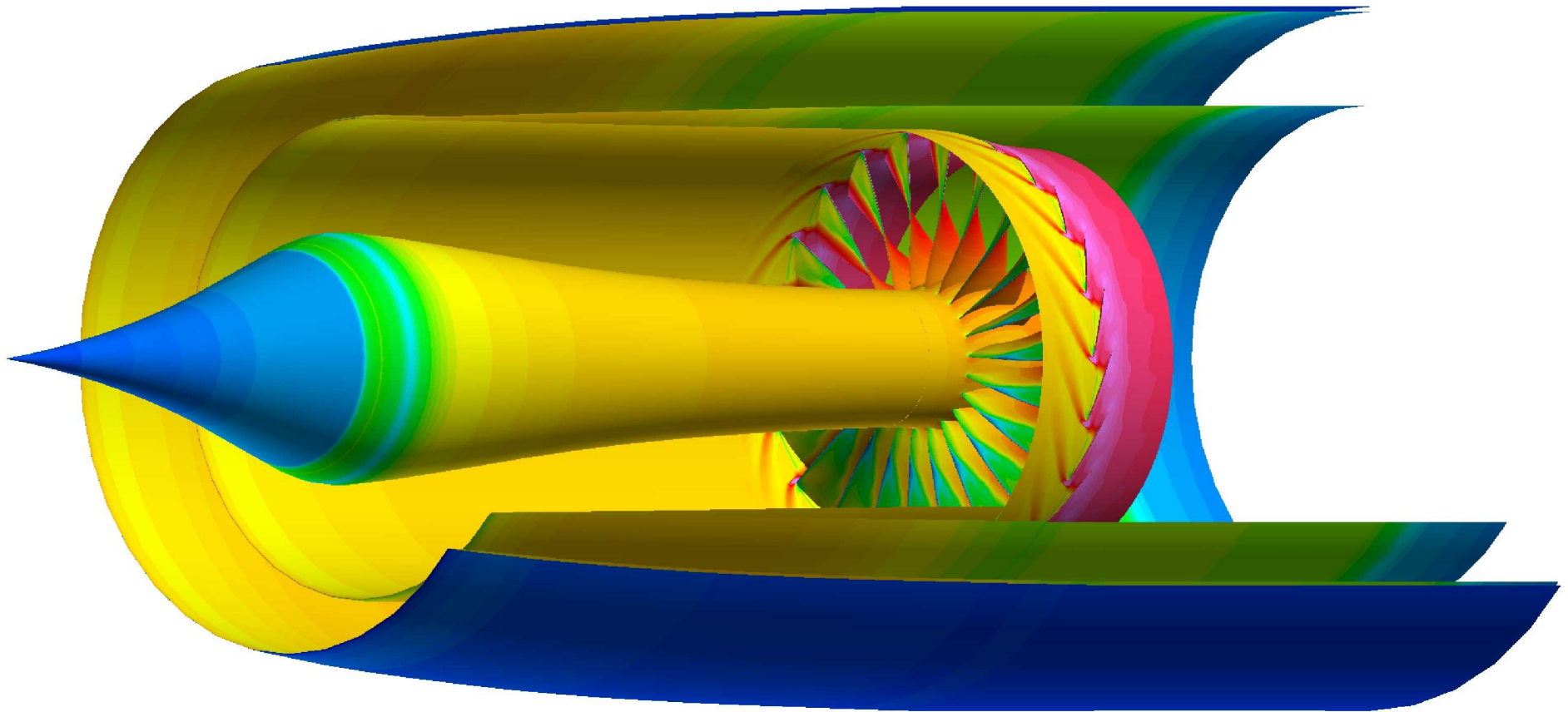

Blade to blade grid at tip

Tip clearance region

Solution details

- Solutions run 10,000 – 20,000 iterations at CFL = 2.5
- Fan pressure ratio and mass flow monitored for convergence
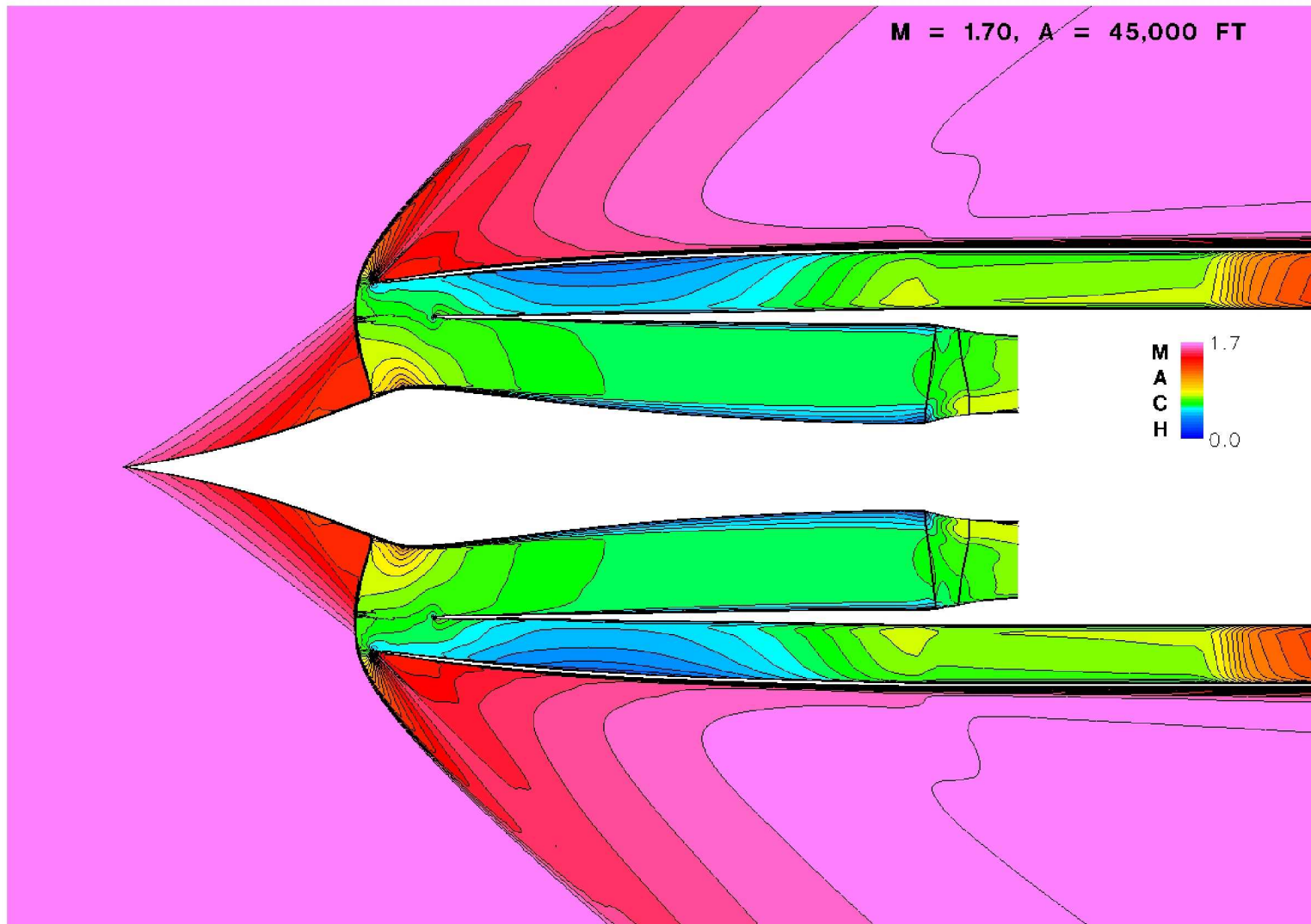- 7 hr. / 10,000 iterations on dual core Xeon CPUs at 3.8 GHz

Static pressure contours
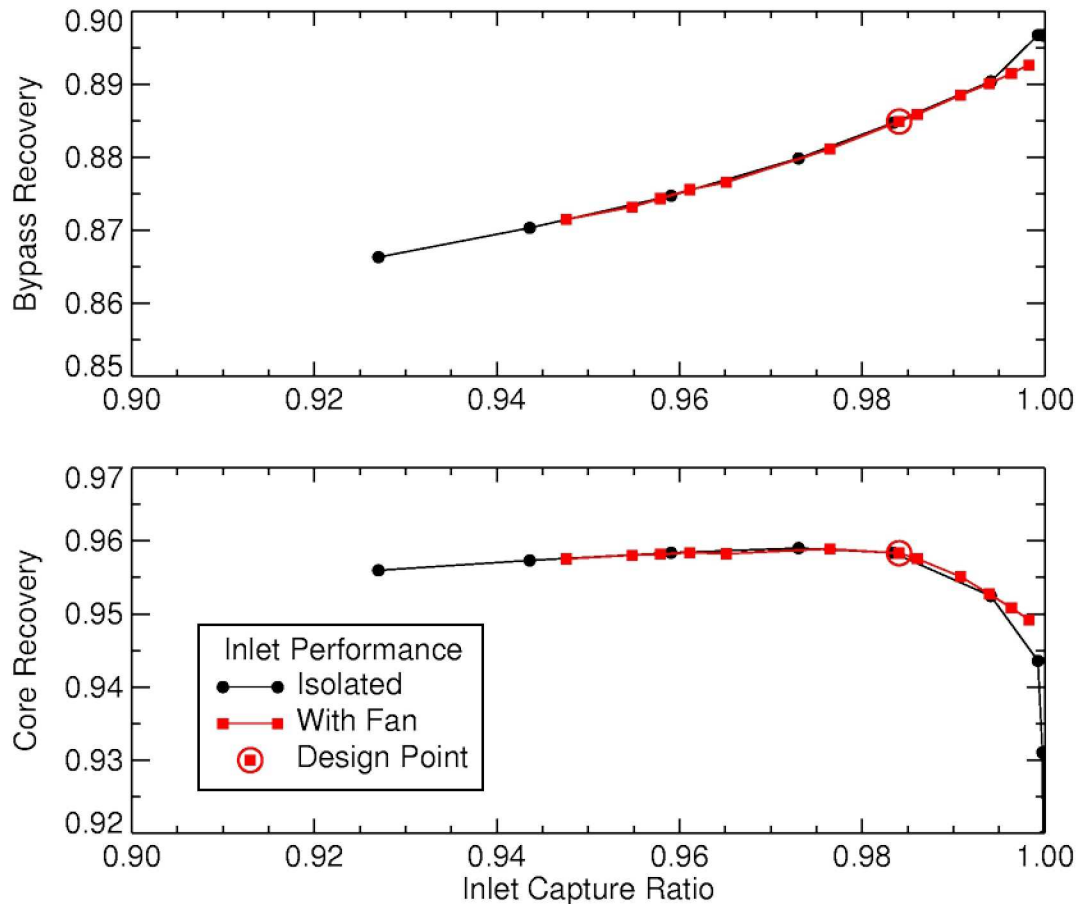

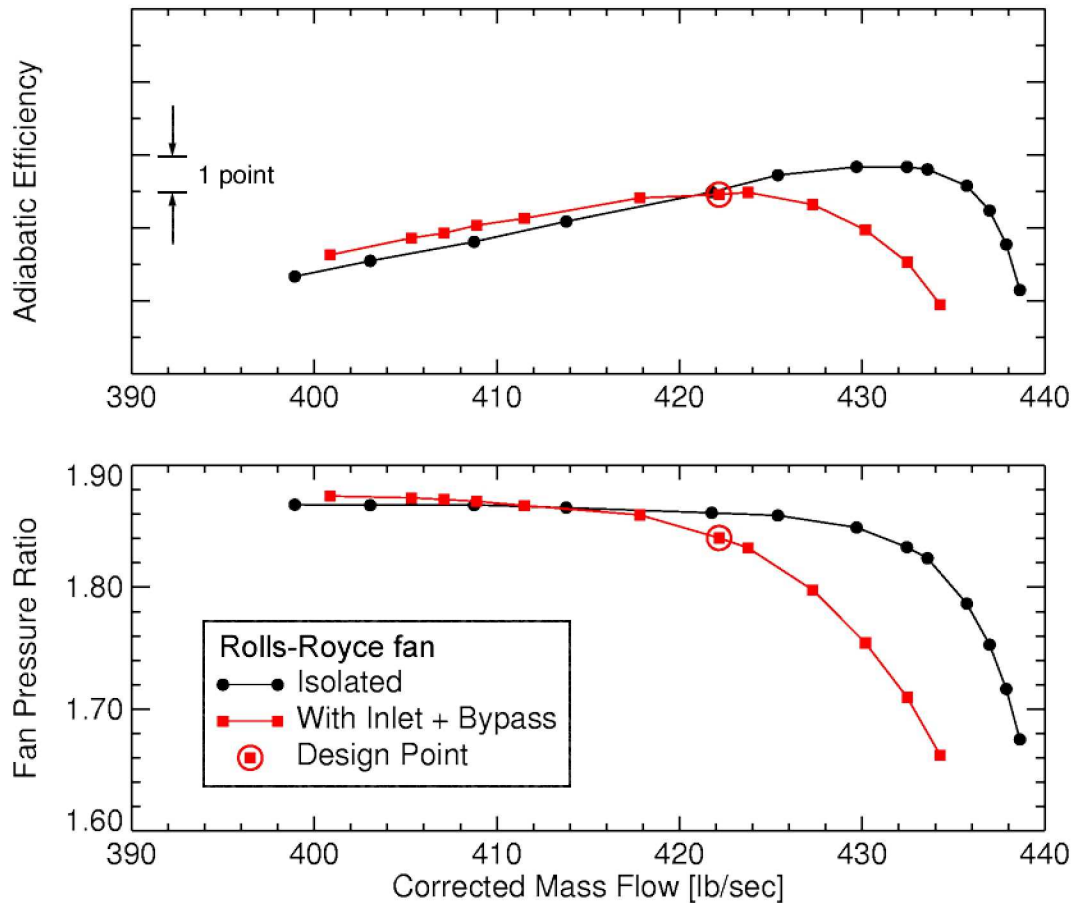- Shocks from fan run upstream into diffuser

M = 1.70, A = 45,000 FT

- Thick diffuser hub boundary layer → fan hub radial distortion

Bypass Capture Ratio and Core Recovery

- Design point: M = 1.7 (over wing) at 45,000 ft.
- Spillage = 1.6 %
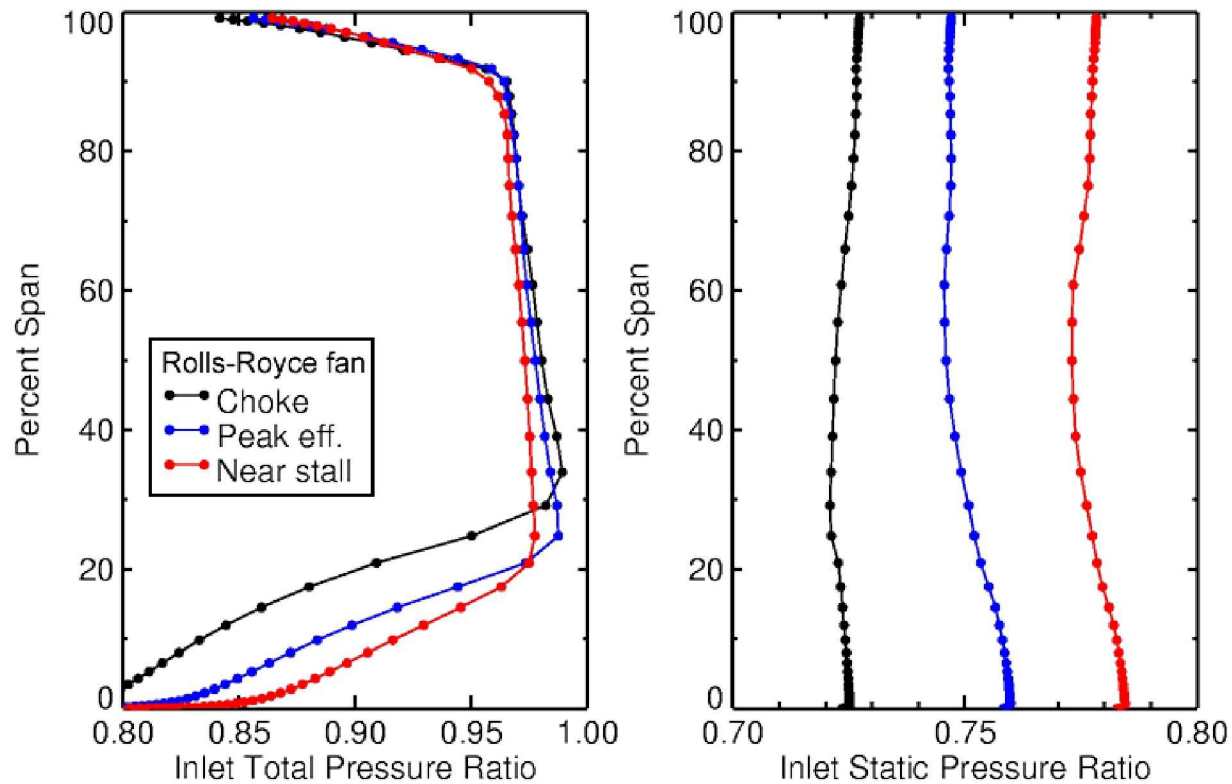- Bypass recovery = 0.885
- Core recovery = 0.96

Fan Efficiency and Pressure Ratio

- Hub distortion reduces maximum mass flow by 2.4 %
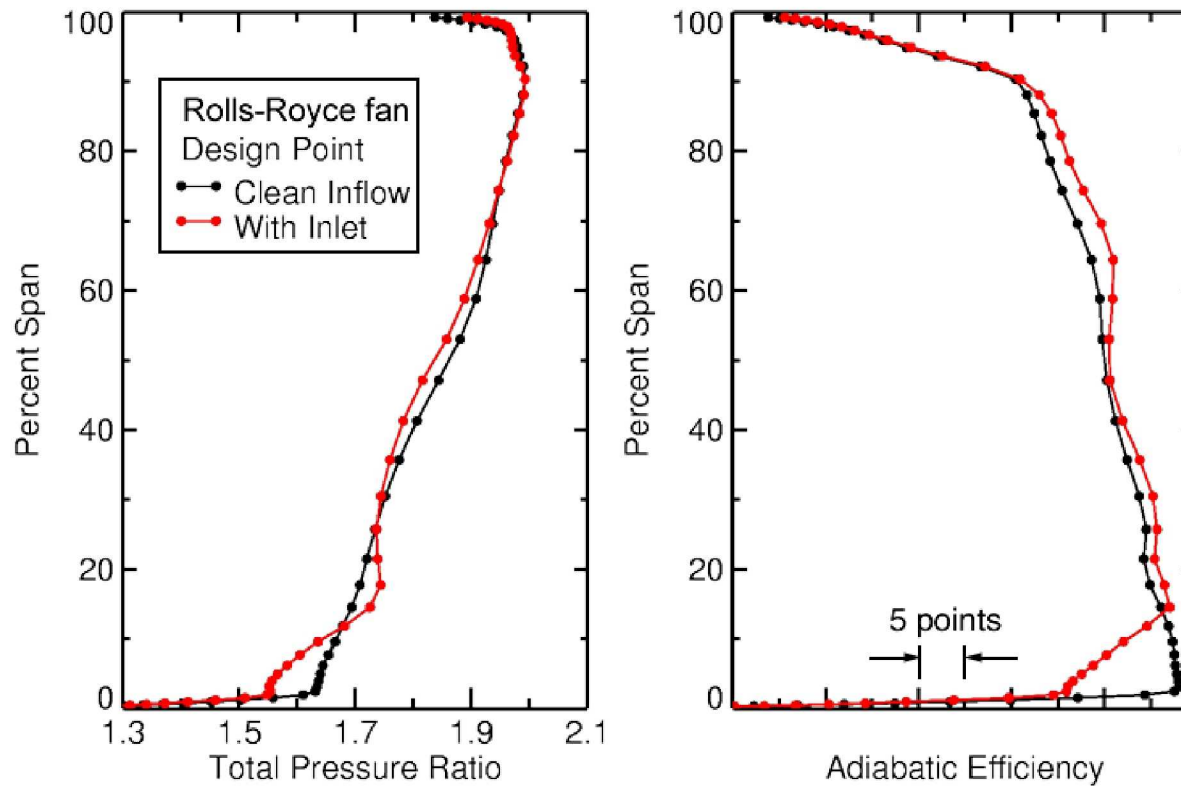 and peak efficiency by 0.8 points

Spanwise profiles at AIP

- Minimal tip distortion due to bypass design
- Large hub distortion − uncommon for fans
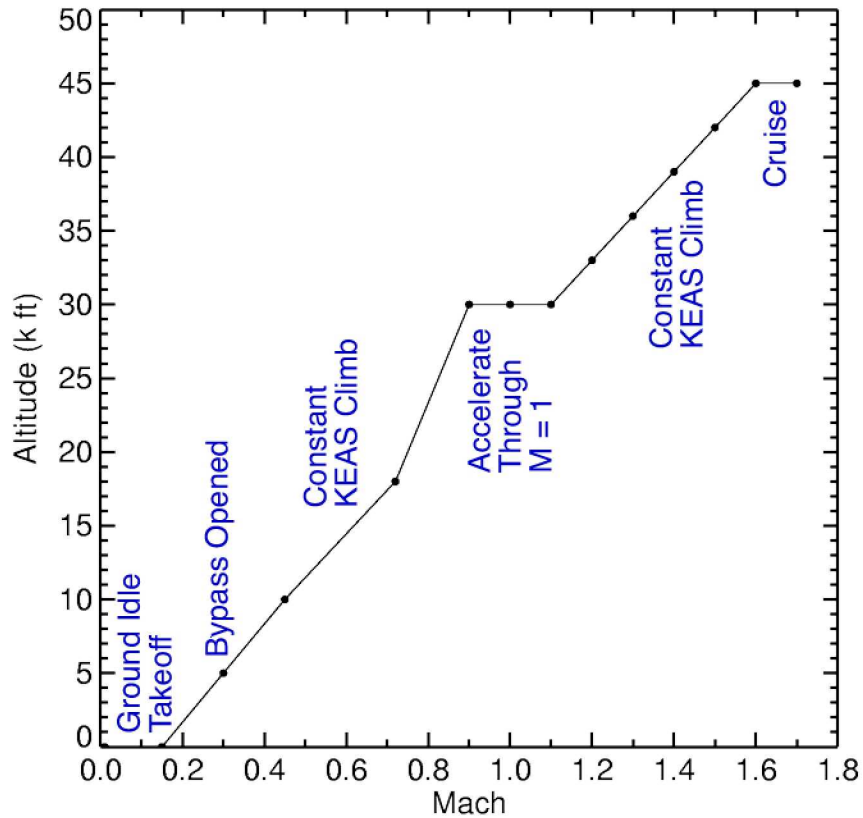- Ps ≈ constant, good BC for isolated inlet calculations

- Hub distortion persists through the fan.
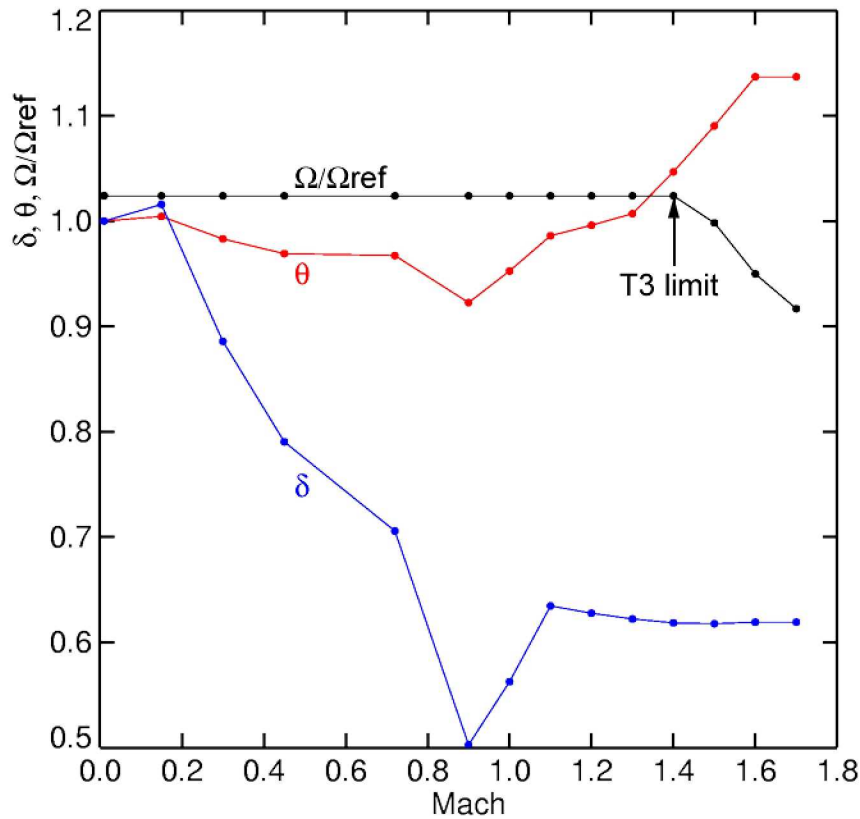 Effects on core compressor are unknown.

Nominal Flight Profile

Coupled inlet / fan calculations made at each point shown on flight profile

Fan Corrected Conditions

$$\theta = T_0 / T_{0,SLS}$$

$$\delta = P_0 / P_{0,SLS}$$

$$\dot{m}_c = \dot{m}\sqrt{\theta} / \delta \qquad \text{Corrected flow}$$

$$N_c = \Omega / \sqrt{\theta} \qquad \text{Corrected speed}$$

$$PR = P_{02} / P_{0,AIP} \qquad \text{Pressure ratio}$$

Boundary Conditions

Upstream

- Subsonic: P_0, T_0 specified, R^- extrapolated from interior
- Supersonic: all quantities specified

Downstream and bypass exit

- Bypass closed for M < 0.3
- Subsonic: Ps specified
- Supersonic: all quantities extrapolated

Freestream

- Characteristic perturbation about freestream
- Reynolds number varies with altitude: $\mathrm{Re} = f(P_{0\infty}, T_{0\infty})$

Fan

- Corrected speed varies with altitude: $Nc = \Omega\sqrt{\theta}$
- Ω = constant over most of flight profile
- Ω reduced for M > 1.4 due to T3 limit based on cycle deck data from GAC
- Ps = linear with Nc, matched to desired mass flow at 2 operating points
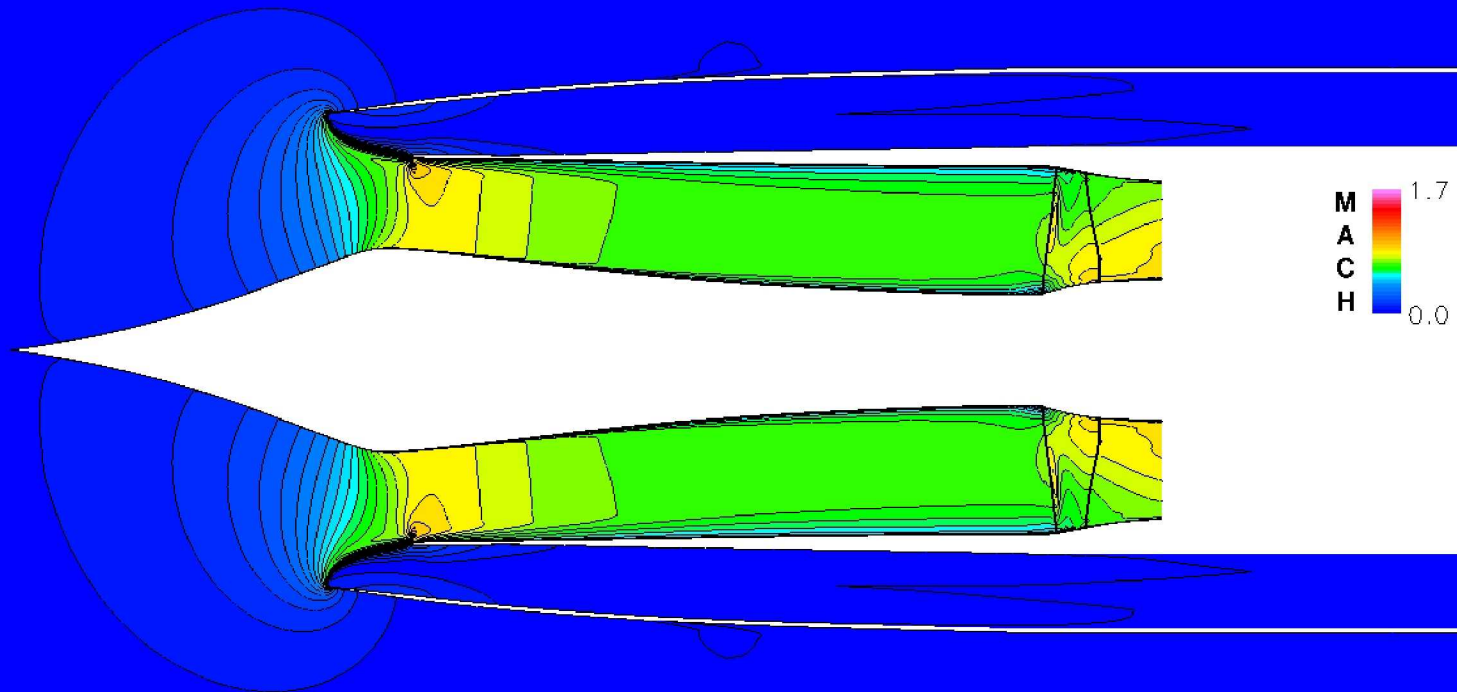
Mach Contours

The following slides show Mach contours at most points on the flight profile.
• Note boundary layers at fan face, bypass choking, and shock structure.
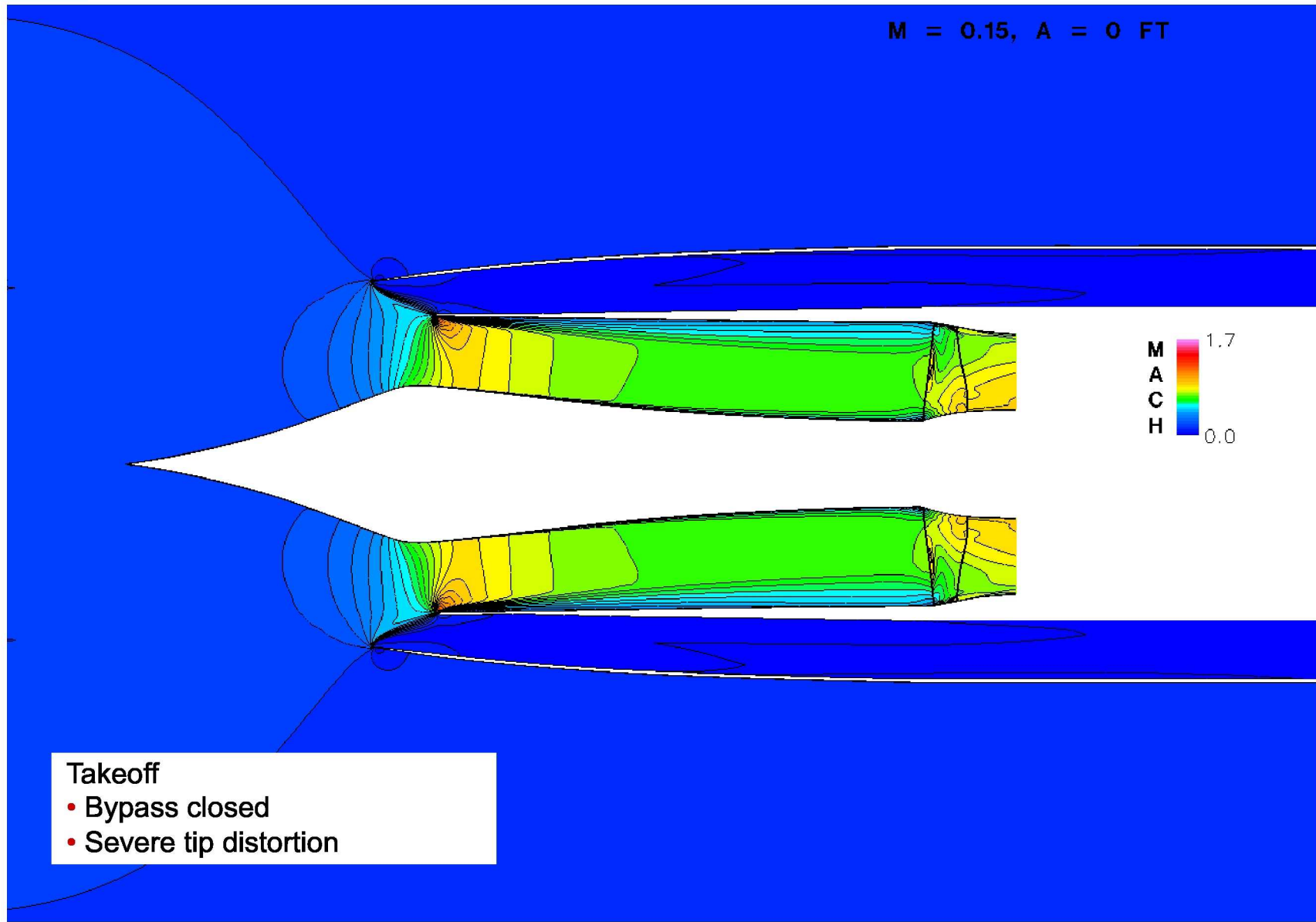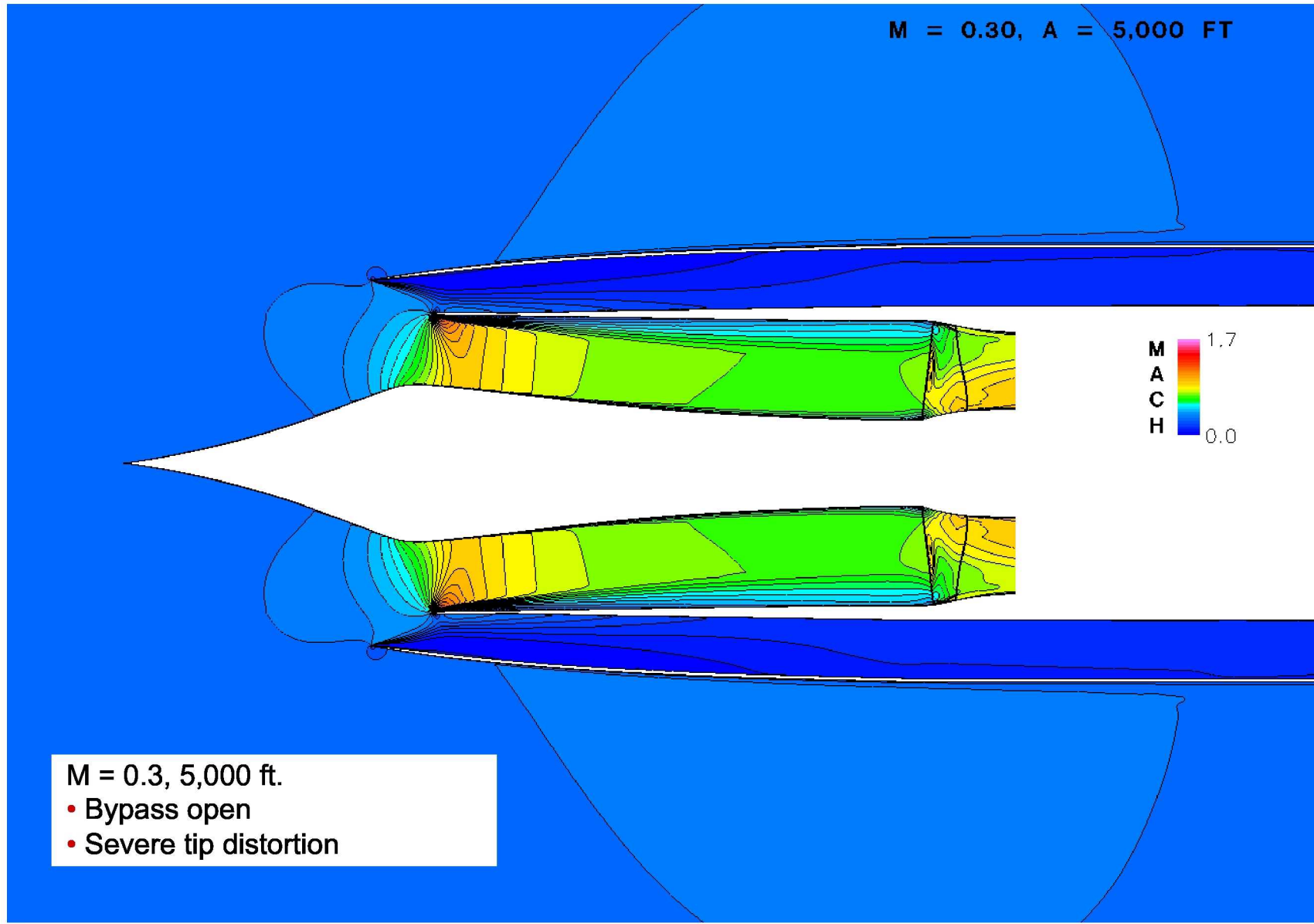
Mach Contours

M = 0.01, A = 0 FT

MACH 1.7 0.0

Ground idle
- Bypass closed
- Moderate tip distortion

Mach Contours

M = 0.15, A = 0 FT

MACH
1.7
0.0

Takeoff
- Bypass closed
- Severe tip distortion

Mach Contours

M = 0.30, A = 5,000 FT

MACH 1.7 — 0.0

M = 0.3, 5,000 ft.
- Bypass open
- Severe tip distortion

Mach Contours

M = 0.45, A = 10,000 FT

MACH 1.7 ... 0.0

M = 0.45, 10,000 ft.
• Diffuser choked
• Moderate tip distortion

Mach Contours

M = 0.72, A = 18,000 FT

MACH 1.7 — 0.0

M = 0.72, 18,000 ft.
• Bypass nearly choked
• Low tip distortion

Mach Contours

M = 0.90, A = 30,000 FT

MACH 1.7 / 0.0

M = 0.90, 30,000 ft.
- Bypass choked
- Shock on shoulder
- Low tip distortion

Mach Contours

M = 1.00, A = 30,000 FT

M = 1.00, 30,000 ft.
- Possible shock on nacelle
- Shock on shoulder
- Low tip distortion

Mach Contours

M = 1.10, A = 30,000 FT

MACH 1.7 ... 0.0

M = 1.10, 30,000 ft.
• Shocks on spike, cowl, shoulder
• Low tip distortion

Mach Contours

M = 1.20, A = 33,000 FT

M = 1.20, 33,000 ft.
- Shocks on spike, cowl, shoulder
- Low tip distortion

Mach Contours

M = 1.40, A = 39,000 FT

M = 1.40, 39,000 ft.
- Shocks on spike, cowl, shoulder
- Low tip distortion

MACH 1.7 — 0.0

Mach Contours

M = 1.60, A = 45,000 FT

MACH 1.7 0.0

Cruise, M = 1.60, 45,000 ft.
• Shocks on spike, cowl, shoulder
• Hub distortion increasing

Mach Contours

M = 1.70, A = 45,000 FT

MACH
1.7
0.0

Over wing, M = 1.70, 45,000 ft.
• Shocks on spike, cowl, shoulder
• High hub distortion
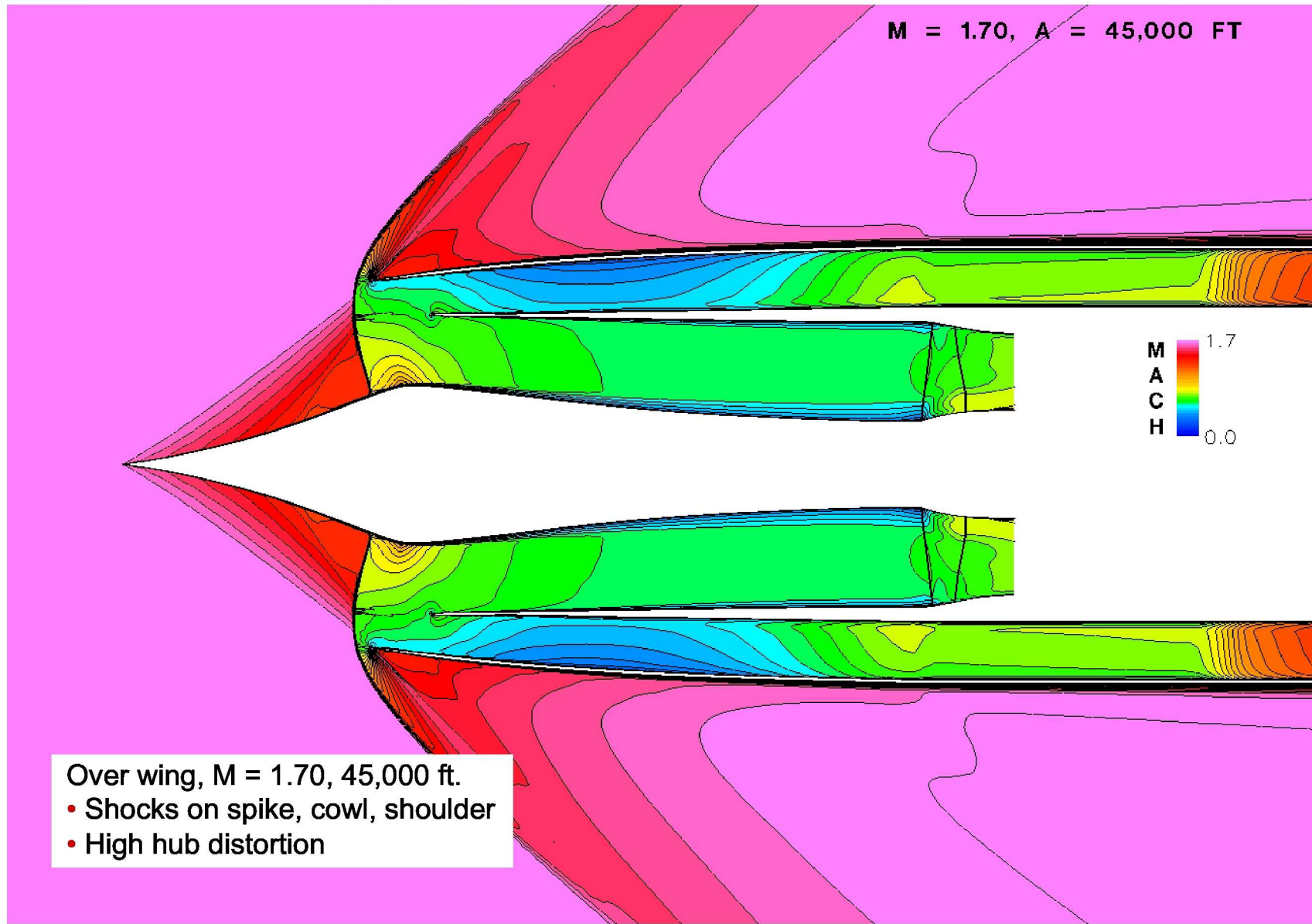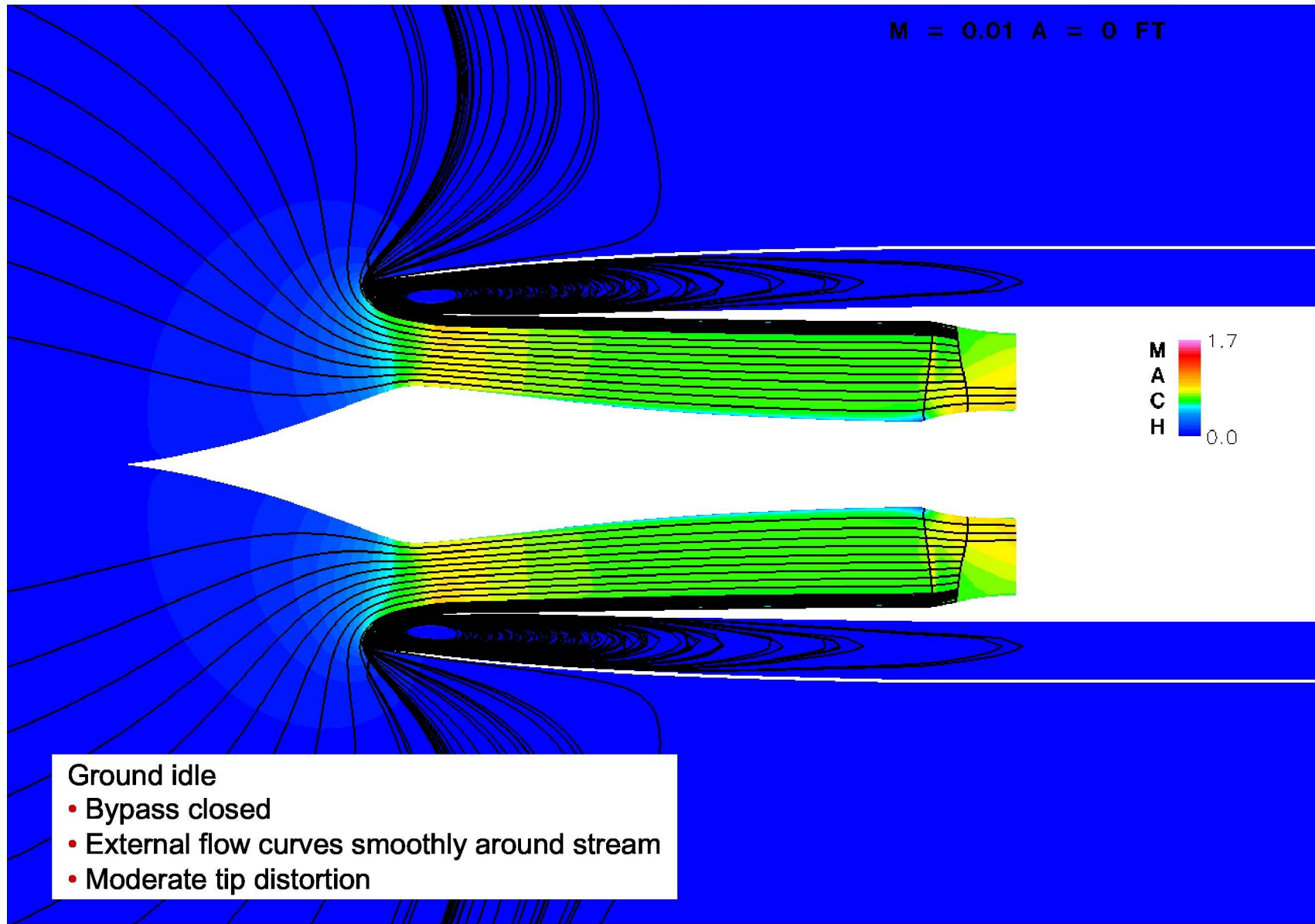
Capture Streamlines

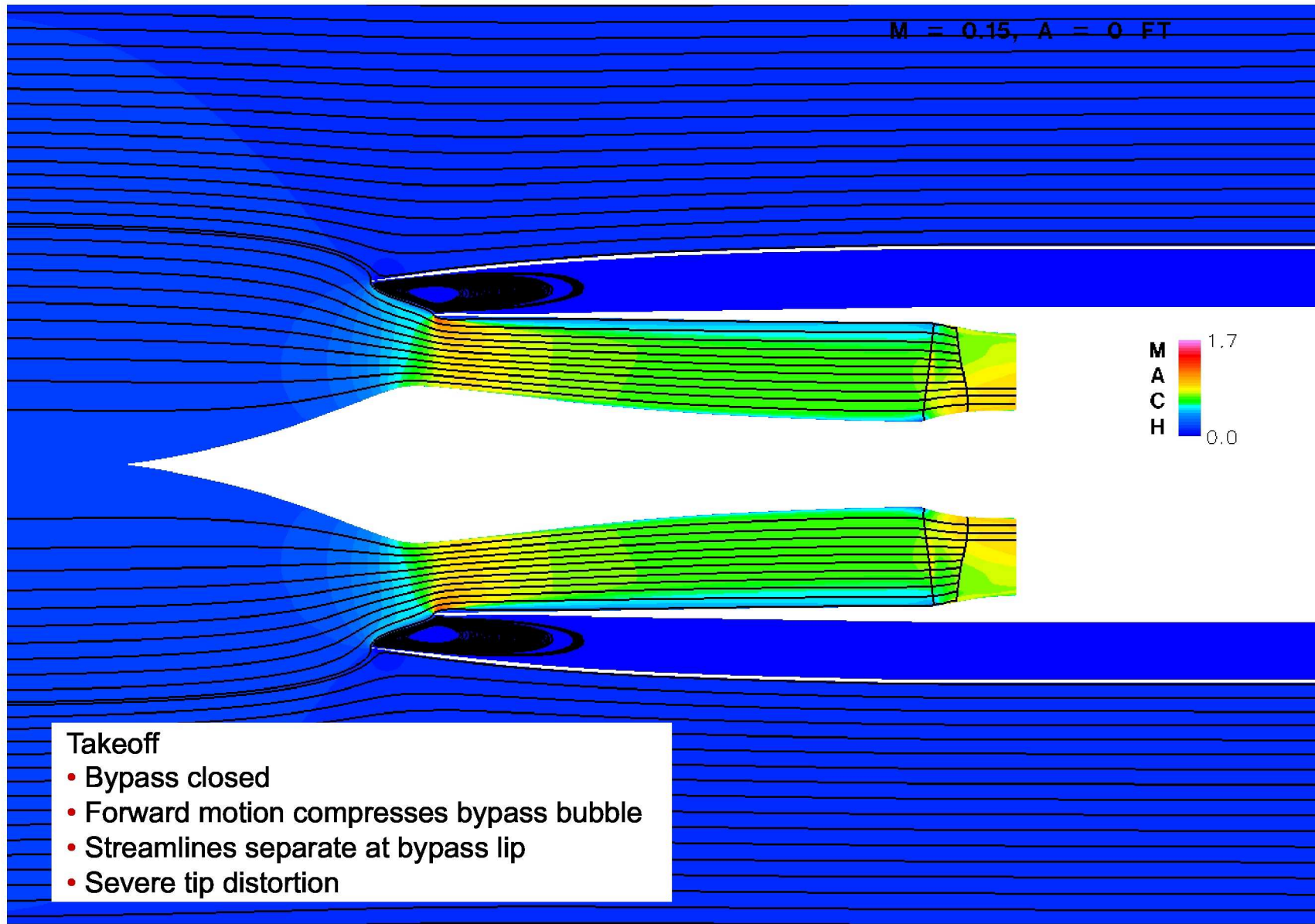The following slides show capture streamlines at some points on the flight profile.
- Note the streamline shape around the bypass splitter lip and the effect on the core tip boundary layer.
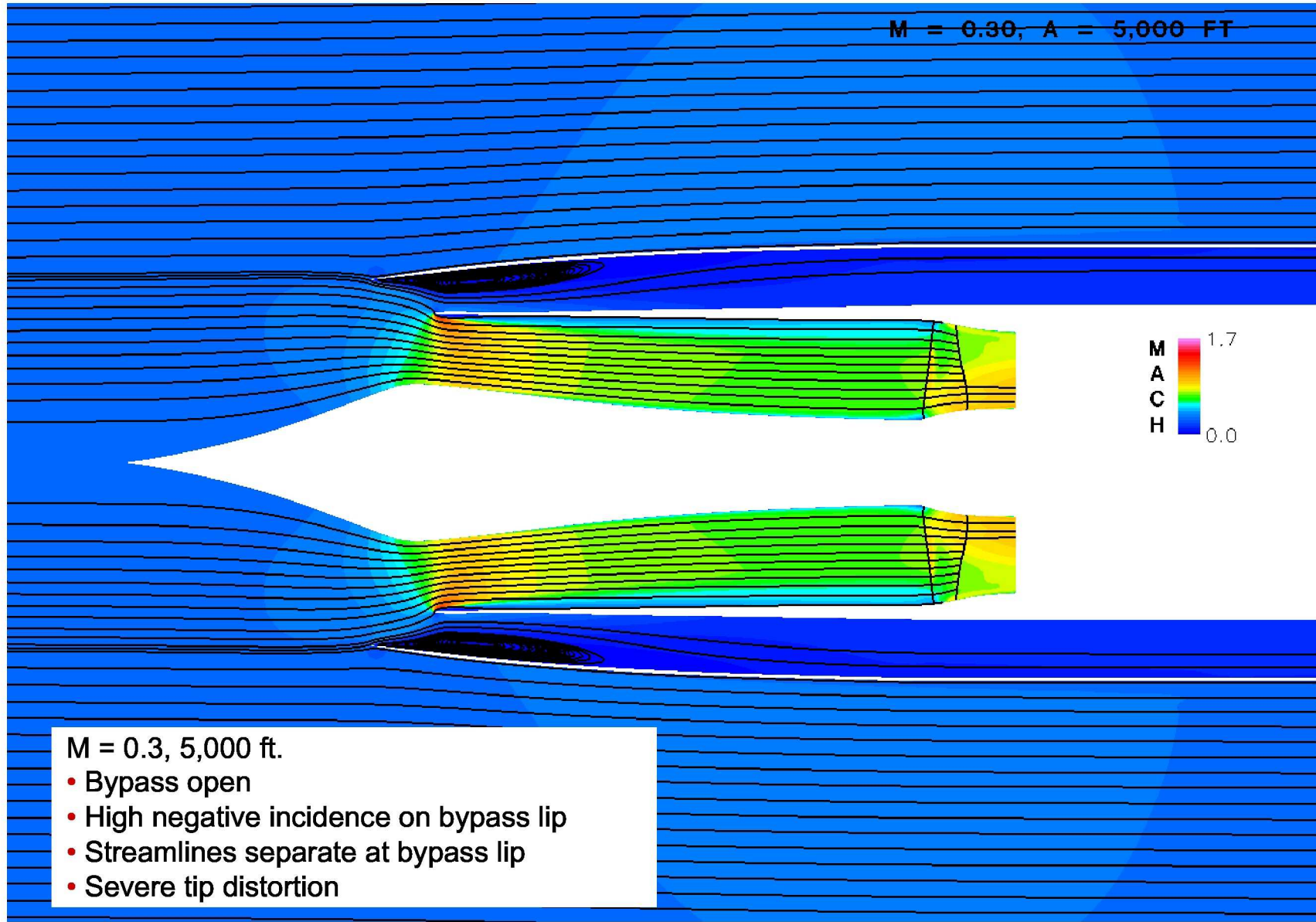
Capture Streamlines

M = 0.01 A = 0 FT

MACH 1.7 — 0.0

Ground idle
- Bypass closed
- External flow curves smoothly around stream
- Moderate tip distortion

Capture Streamlines

M = 0.15, A = 0 FT

MACH
1.7
0.0

Takeoff
- Bypass closed
- Forward motion compresses bypass bubble
- Streamlines separate at bypass lip
- Severe tip distortion

Capture Streamlines

M = 0.30, A = 5,000 FT

MACH 1.7 — 0.0
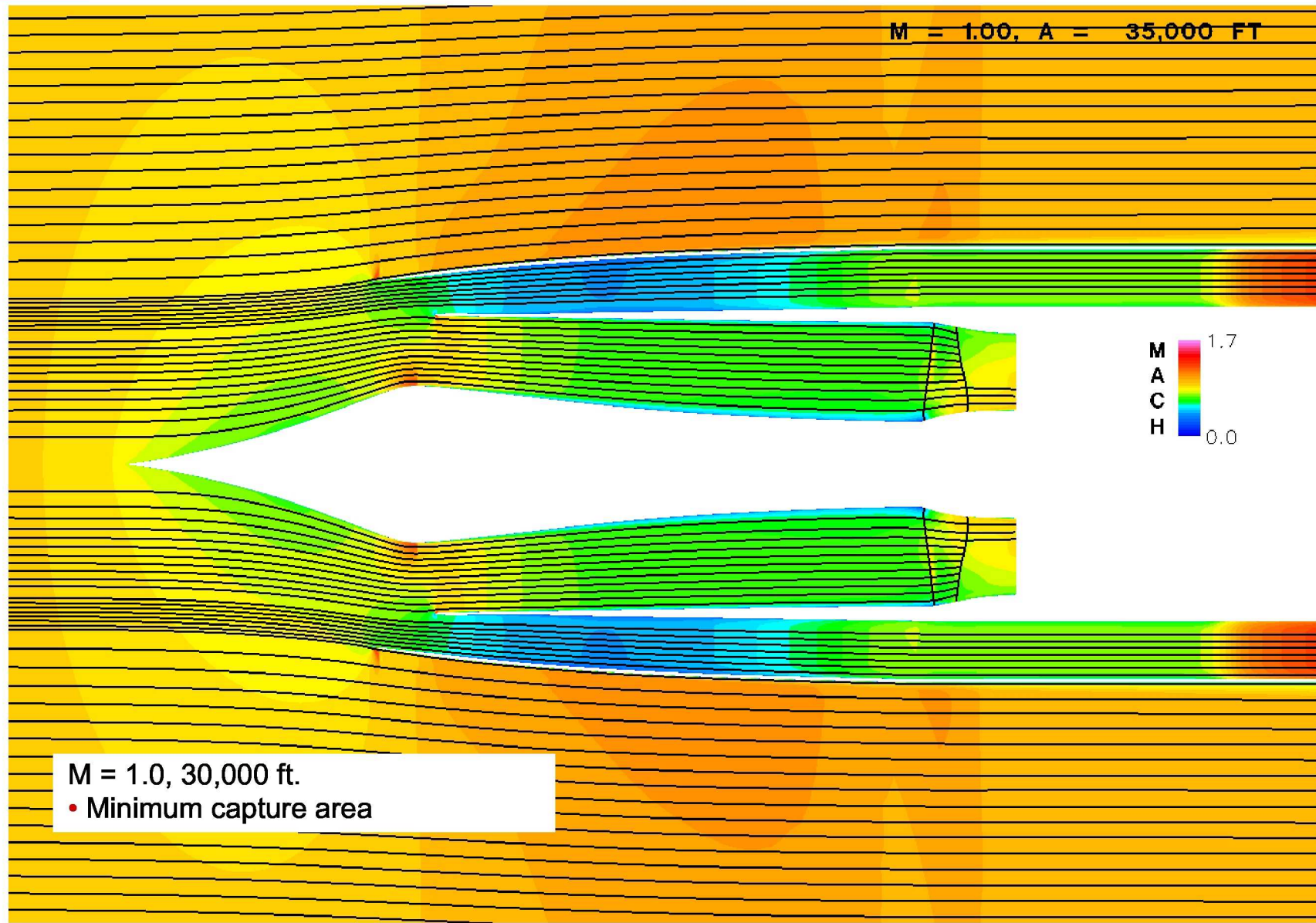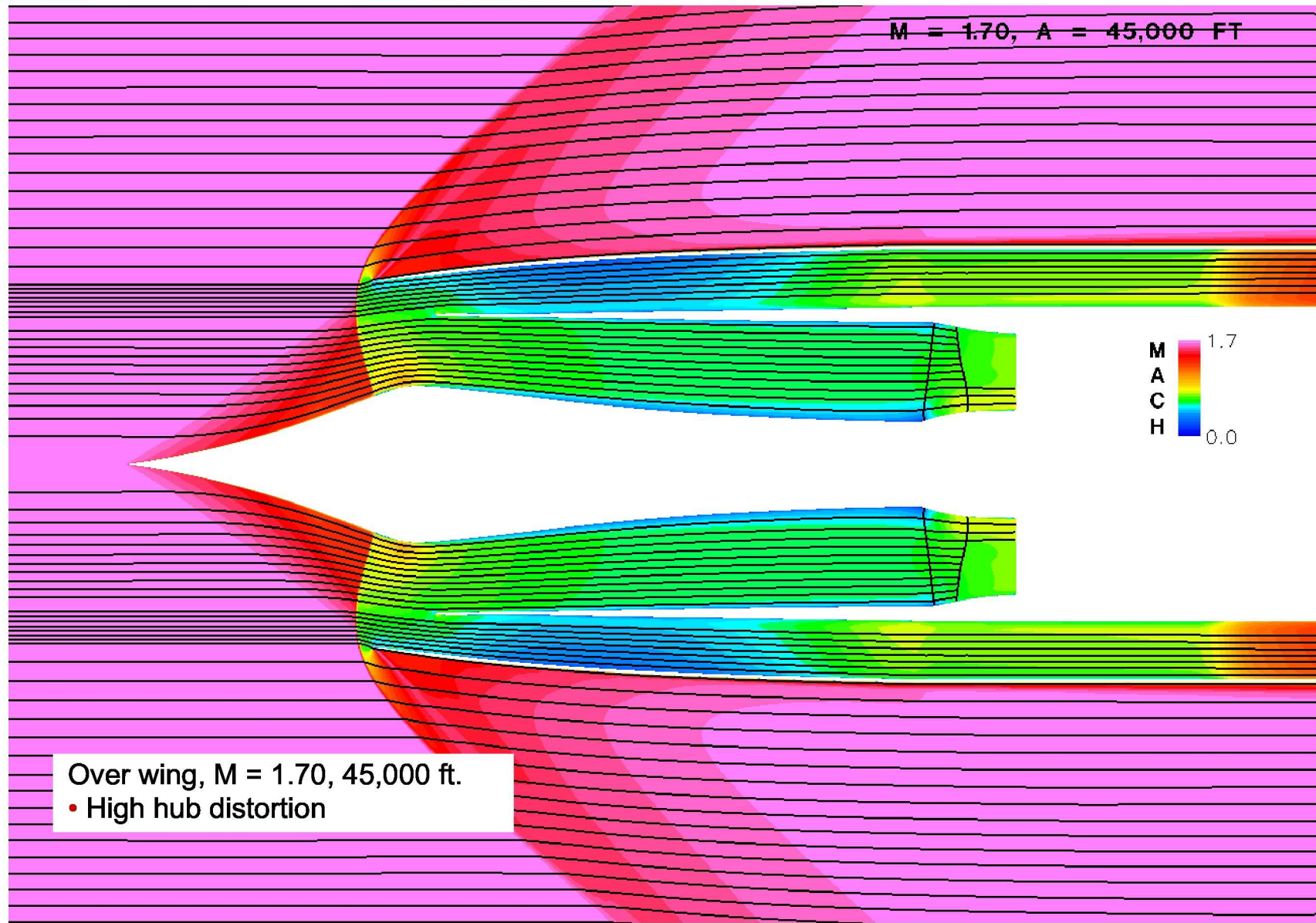
M = 0.3, 5,000 ft.
- Bypass open
- High negative incidence on bypass lip
- Streamlines separate at bypass lip
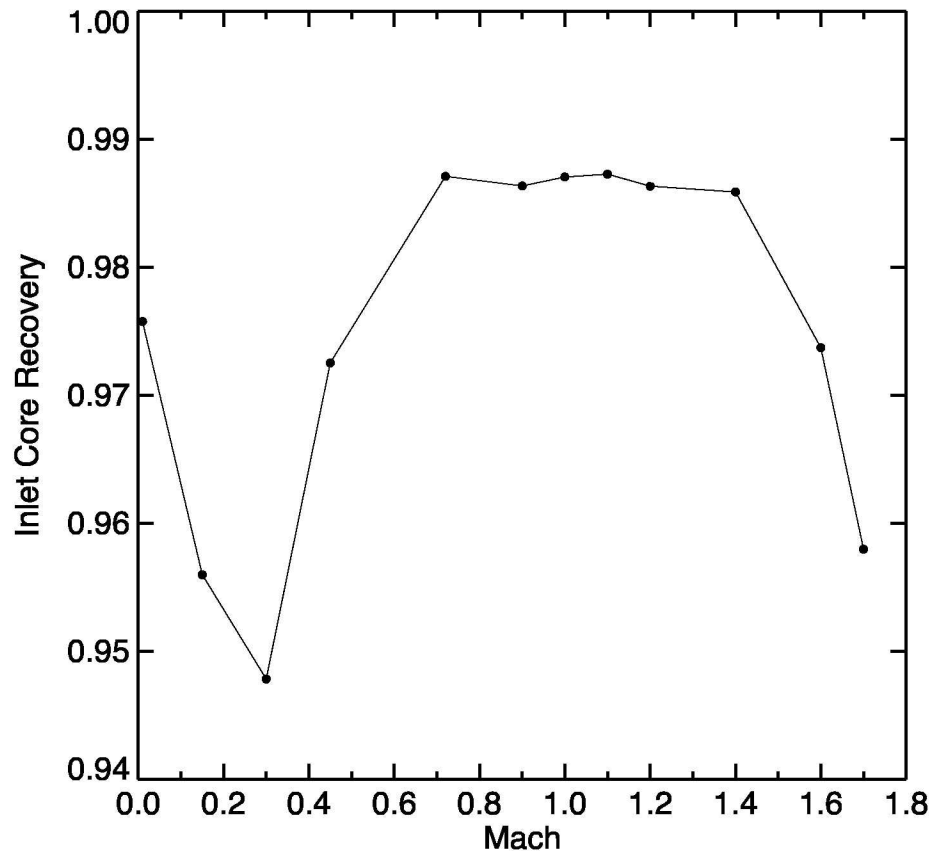- Severe tip distortion

Capture Streamlines

M = 1.00, A = 35,000 FT

MACH 1.7

MACH 0.0

M = 1.0, 30,000 ft.
• Minimum capture area

Capture Streamlines

M = 1.70, A = 45,000 FT

MACH 1.7
0.0

Over wing, M = 1.70, 45,000 ft.
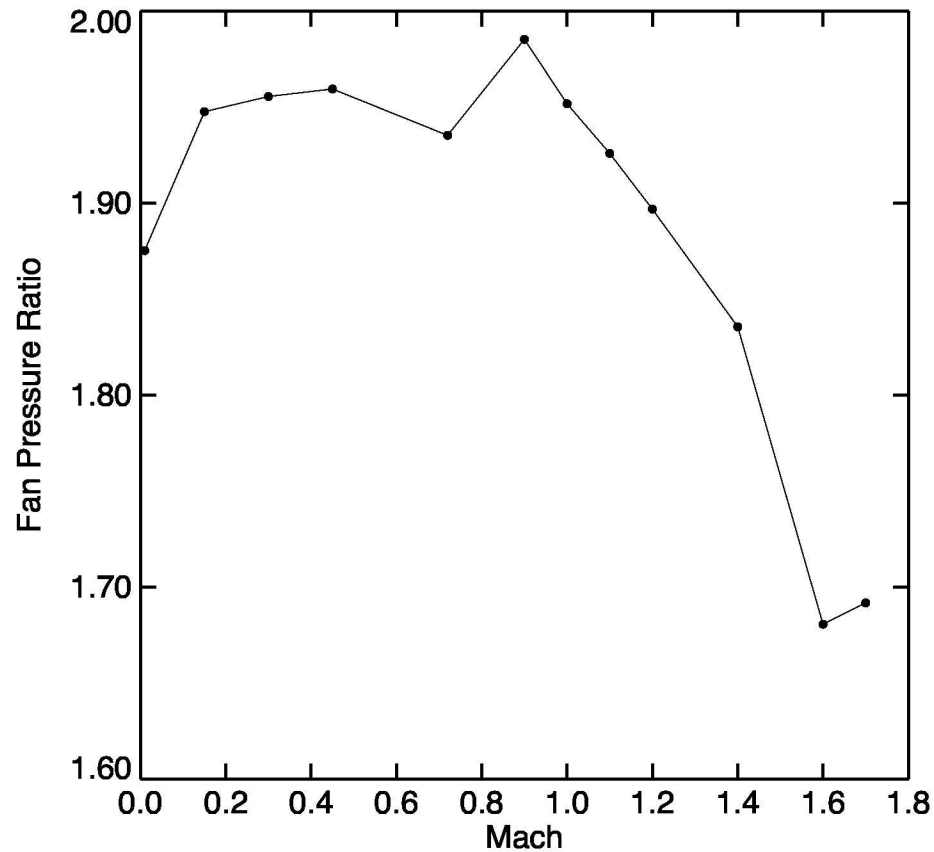• High hub distortion

Inlet Core Recovery

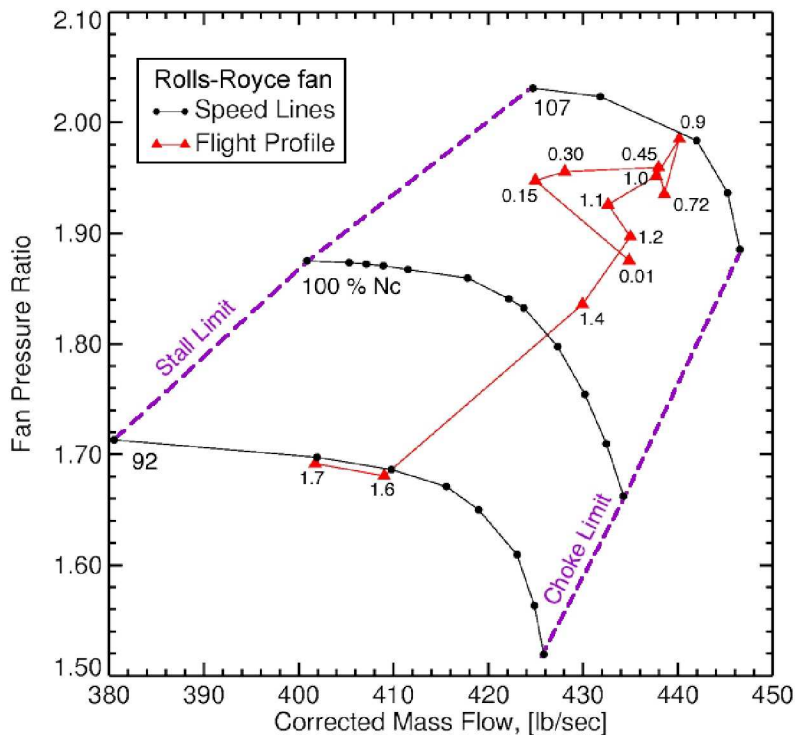

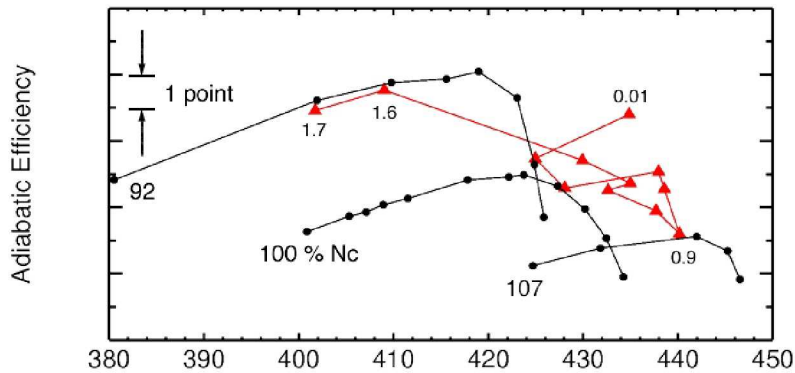- Inlet recovery is low at M < 0.7 due to bypass separation
- Recovery is excellent for 0.7 < M < 1.4
- Recovery decreases with M > 1.4 due to shock losses

Fan Pressure Ratio

- Fan pressure ratio varies with corrected speed
- Decreases for M > 1.4 due to reduced Ω

Fan Pressure Ratio and Efficiency Maps

- 3 speed lines shown for fan with cruise distortion profile.
- Fan operating line is nearly linear except for low Mach numbers.
- Nc varies between 92 and 107 % of design.
- M = 0.15 – 0.3 is close to the stall line due to high tip radial distortion.
- Fan PR drops with Nc for M > 1.4.
- Fan operates near peak η at cruise.

Conclusions

Two coupled CFD codes were used to model the interaction between a supersonic Gulfstream inlet and a Rolls-Royce fan.

Advantages of coupled analysis
- Eliminates modeling at interface
- Can track inlet distortion effects all the way through the fan
- Hard to model isolated components for some cases, e.g. low Mach nos.

Disadvantages
- Increased grid / solver complexity
- Longer solutions times

Gulfstream inlet / Rolls-Royce fan
- Design point: good inlet recovery, fan operates near peak efficiency.
- Hub radial distortion passes through fan, may cause problems for the core.
- Flight profile: stable operation at all operating points.
- Identified reduced stall margin at low Mach nos. due to bypass lip separation. Lip redesign is being studied.

- 2 papers at AIAA 48th Aerospace Sciences Meeting, Jan. 4-7 2010, Orlando, FL