Jet Engine Inlet Design

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Topics

- Subsonic Inlets
- Flow Patterns
- Internal Flow
- External Flow
- Inlet Performance Criteria
- Supersonic Inlets
- Reverse Nozzle Diffuser
- Shock Boundary Layer Problem
- External Deceleration
- Flow Stability Problem

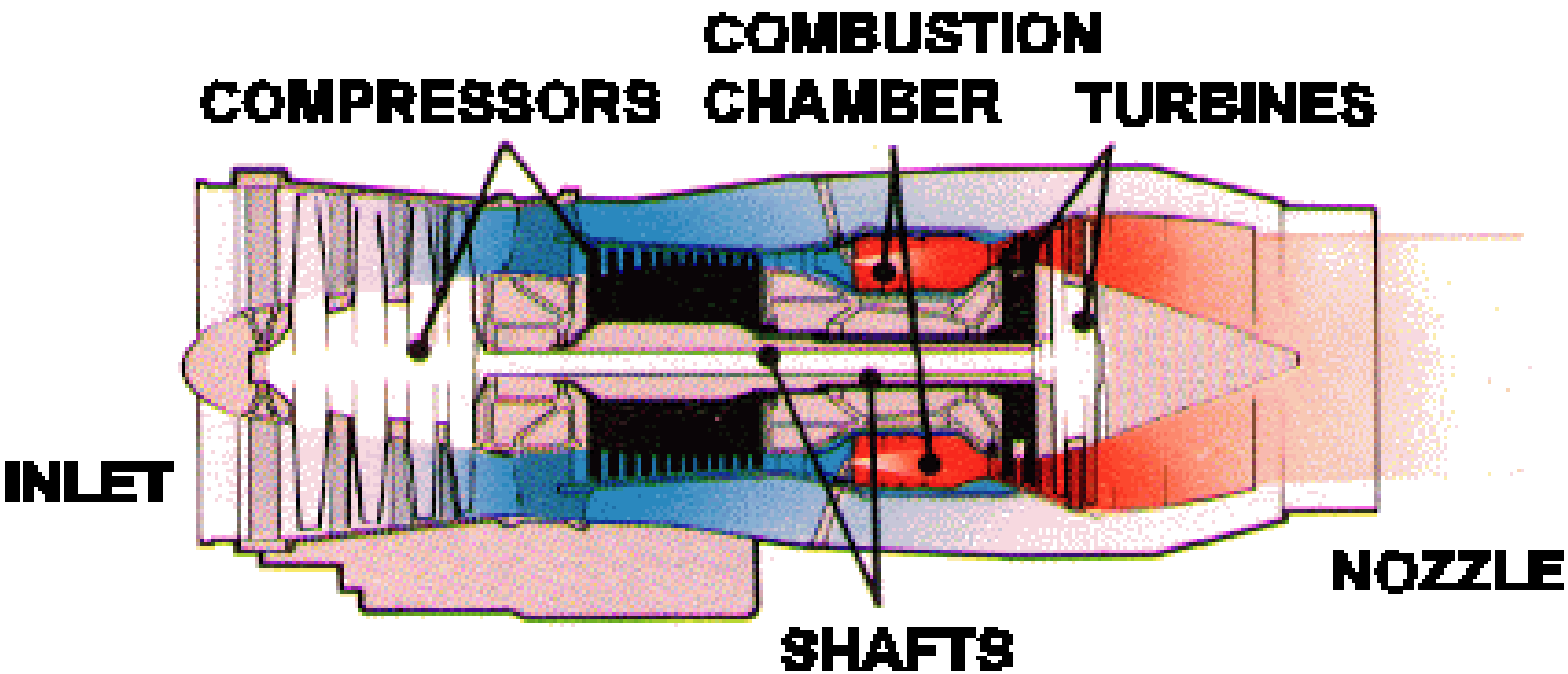
Design Objectives

- Prevent boundary layer separation
- Lower sensitivity to pitch and yaw
- Minimize stagnation pressure loss
- Produce uniform flow velocity and direction
- Increase efficiency operation in both supersonic and subsonic
- Reduce flow distortion at engine fan face
- Increase pressure recovery

Jet Engine Components

- Inlet-sucks in air
- Compressor-squeezes the air
- Combustor-adds heat to the air
- Turbine-provides work for the squeezing process
- Nozzle-blows the air out the back

Engine Layout



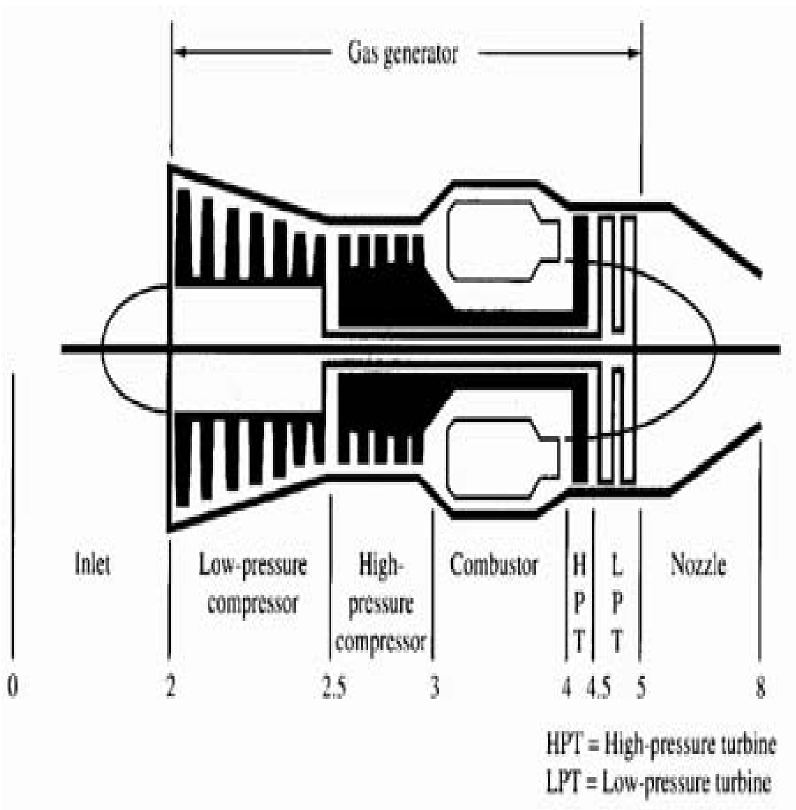
Inlet

- Sucks in air
- Slows air down
- Feeds air into compressor and fans

Inlet Air Flow

- Subsonic
- Supersonic-use shock wave to slow down air

Air-Breathing Engines



- Based on Gas generator

Types of Air-Breathing Engines

- Turbojet
- Turbofan
- Afterburning Turbofan
- Turboprop/ shaft
- Ramjet
- Scramjet
- Turbojet/Ram jet

Various Inlet Models

- Ramjet
- Scramjet
- Turbojet/Ramjet Combo

Ramjet

- Ramjet
  - –Incoming high speed air
  - –Compressed by ram effect
  - –For high enough air speed, no compressor or turbine needed

Scramjet

- Scramjet
  - Supersonic Combustion Ramjet
  - Air mixed with fuel while traveling at supersonic speeds
  - Temp increase and pressure loss due to shocks are greatly reduced

Pulse Jets

- Pulse Jets
  - Series of spring-loaded shutter type valves before compressor
  - Valves close to prevent backflow

Background & Motivation

- Pressure and/or velocity flow distortions at engine (compressor) fanface can compromise engine efficiency.
- Separation of incoming boundary-layer flow can reduce pressure recovery and lead to:
  - Unsteady loading
  - Increased fatigue of engine fan blades
  - Aerodynamic stall on compressor blades[1]

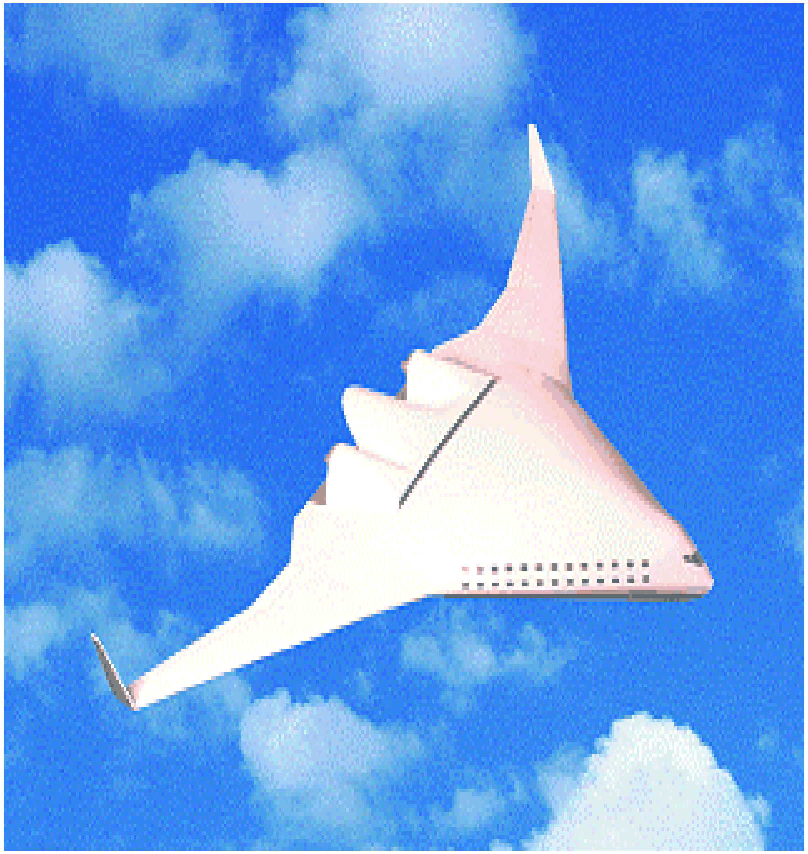
Integrated Propulsion Systems

- Joint Strike Fighter

- NASA/Boeing, Blended Wing Body

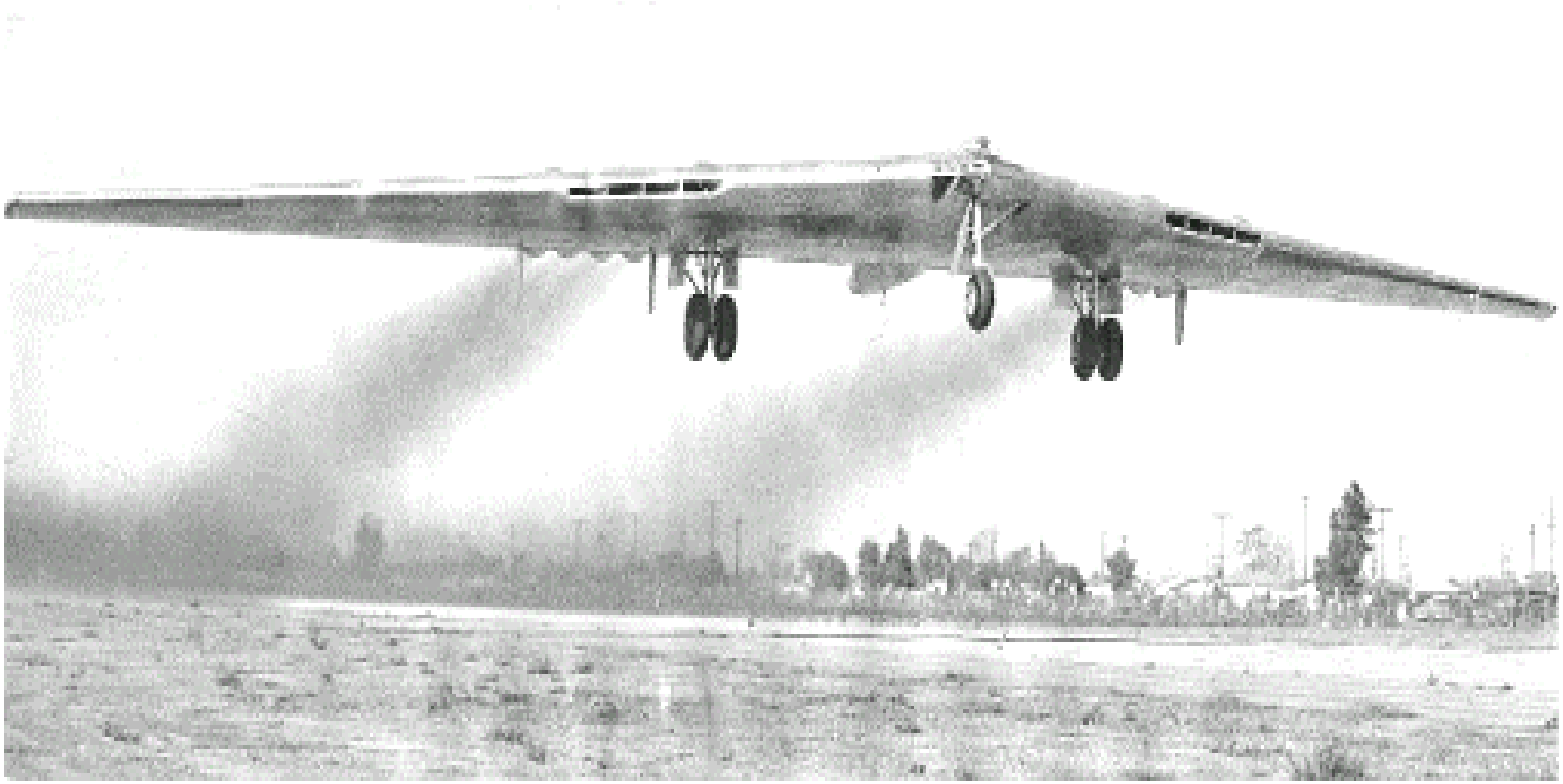
Boeing JSF X-32B
Joint Strike Fighter

Blended Wing Body



- Engine inlets located at the aft end of aircraft
- Developing large boundary layer upstream of engine inlet

YB-49 Northrop
Blended Wing Body



Subsonic Inlets

- Inlet operates with a wide range of incident stream conditions
- due to flight speed and the mass flow demand by the engine

Inlet Area

- chosen to minimize external acceleration during takeoff
- Upstream area is less than inlet area

Compressor Inlet Conditions

- Stagnation Temperature

  $T_{02}=T_a(1+M^2(k-1)/2)$

- Stagnation Pressure

  $P_{02}=p_a(1+n_d(T_{02}/T_a)-1))^{k_d/(k_d-1)}$

  n_d=adiabatic diffuser efficiency

Inlet Flow

- Behaves as though in a diffuser
  - Momentum decreases
  - Pressure rises
  - No work

Flow Patterns

- Inlet area often chosen to minimize external acceleration during takeoff
- So that external deceleration occurs during level-cruise operation
- External deceleration requires less internal pressure rise
- Hence, less severe loading of the boundary layer

Internal Flow

- Flow in the inlet behaves like a diffuser or decelerator
- Inlet design depends on:
  - Potential flow calculations
  - Boundary layer calculations
  - Wind tunnel testing to assess inlet performance under a wide range of test conditions

Separation in the Inlet

- Separation may take place in 3 zones
  - External flow zone
  - Along underside of internal flow zone
  - Along upperside of lower wall of internal flow zone
- At high angles of attach, all three zones could be subjected to unusual pressure gradients

External Flow

- Inlet design requires a compromise between external and internal deceleration to prevent boundary layer separation

Boundary Layer Separation in Subsonic Flow

- Subsonic flow over inlet lip
- High velocity causes low pressure region followed by high pressure region
- Causing boundary layer separation

Boundary Layer Separation in Supersonic Flow

- Supersonic flow usually ends in abrupt shock
- Shock wall intersection may cause boundary layer separation

Shock-Boundary Layer Problem

- For strong shock wave
  - $M \geq 1.25$
  - Large pressure gradient near wal
  - Fluid near wall cannot move in main direction
  - Boundary layer separates

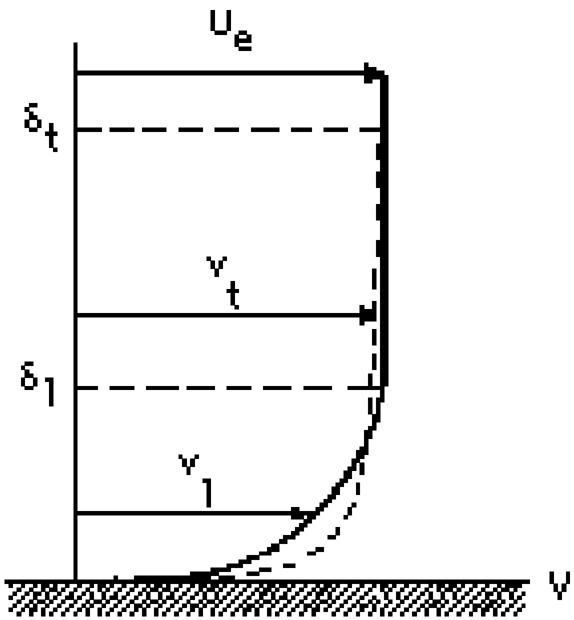
Boundary Layer Separation must be Avoided

- Results in poor pressure recovery in the flow
- Causing extra rearward drag on the body
- Decreasing efficiency

What is a Boundary Layer

- Boundary layers separate from a body due to increasing fluid pressure in the direction of the flow (*adverse pressure gradient)*
- Increase in the fluid pressure increases potential energy of the fluid
- kinetic energy decreases
- Fluid slows and boundary layer thickens
- Wall stress decreases and fluid no longer adheres to the wall

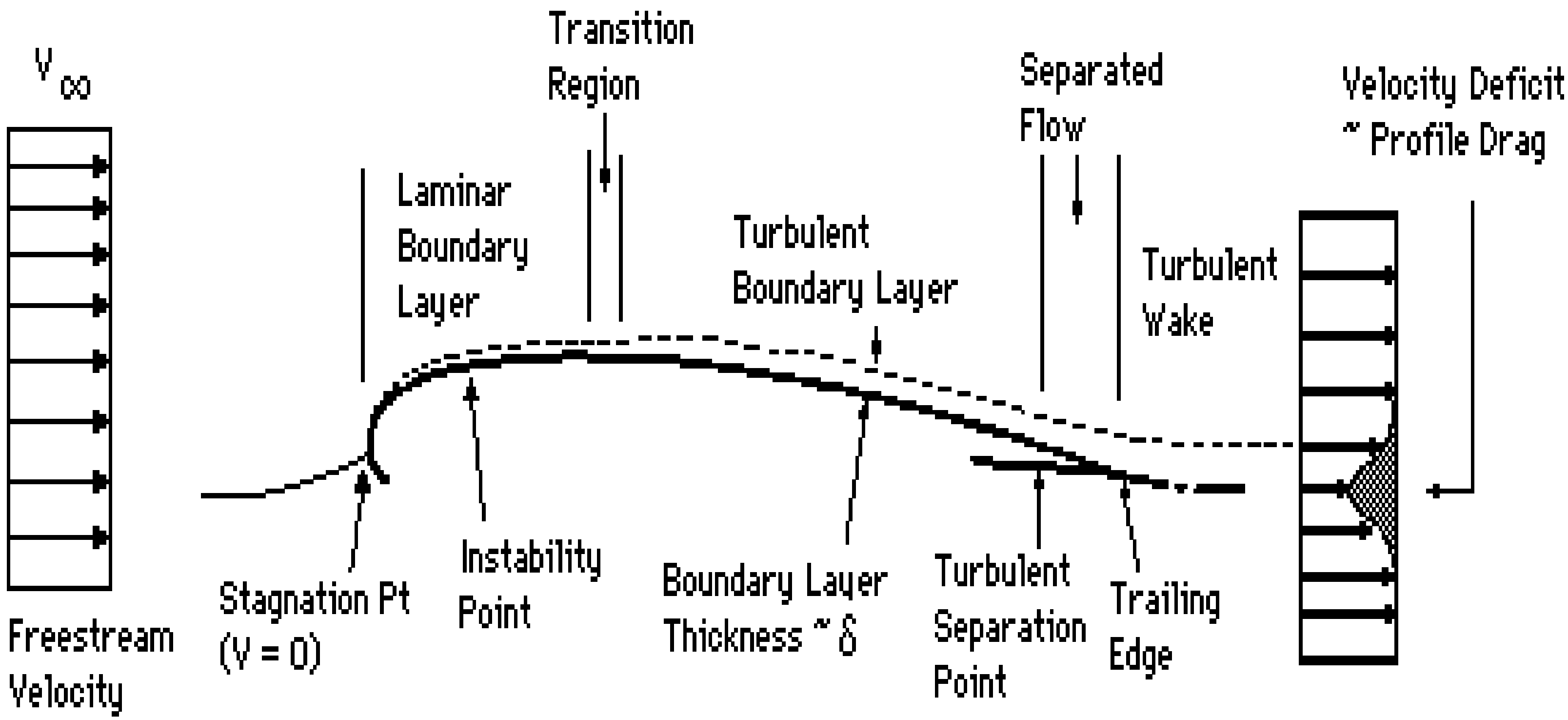
Boundary Layer Velocity Profile



Boundary layer velocity profiles

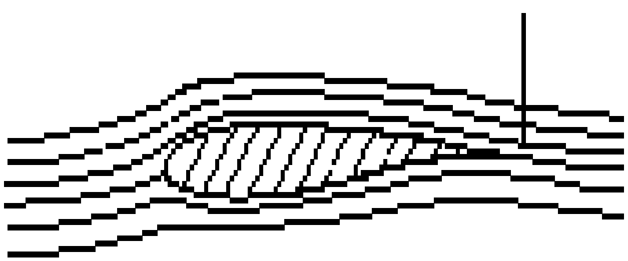
- [2]Boundary layers occur on surface of bodies in viscous flow

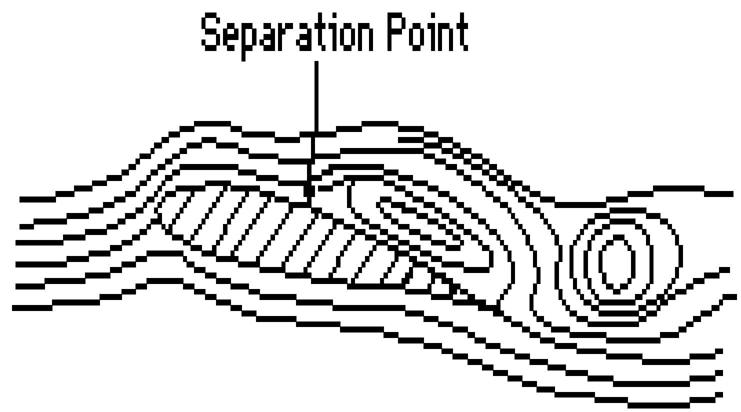
Laminar Boundary Layer



Thickness of boundary layer increases downstream

Viscosity causes boundary layer separation





Consequences of Boundary Layer Separation

- large increase in drag on the body
- Flow distortions

Passive Boundary Layer Control Methods

- Passive
  - Uses vortex generators
  - Supersonic microjets
  - Enhance flow uniformity
  - Boundary layer fluid is energized

Drawbacks to Passive Control Methods

- Drawback
  - Performance is not uniform over entire engine
- Possible Solution
  - Use large number of generators in inlet ducts
- Consequence
  - Additional pressure loss

Active Control Methods

- active flow control scheme
- with feedback control
- Leads to reduced distortion over large parametric range

Separation may occur….

- In zone 1 due to local high velocities and deceleration over outer surface
- In zone 2 or zone 3 depending on the geometry of the duct and the operating conditions

Inlet Performance

- Depends on the pressure gradient on both internal and external surfaces
- External pressure rise is fixed by:
  - external compression
  - Ratio of $\frac{\text{Area Max}}{\text{Area Inlet}}$
- Internal pressure rise depends on the reduction of velocity
  - between entry to the inlet diffuser and entry to compressor

Inlet Performance Criteria

- Isentropic Efficiency
- Stagnation pressure ratio

Isentropic Efficiency

$$\eta_d := \frac{h_{02 \cdot s} - h_a}{h_{0a} - h_a}$$

$$\eta_d := \frac{T_{02 \cdot s} - T_a}{T_{0a} - T_a}$$

$$\eta_d := \frac{\left(\frac{p_{02 \cdot s}}{pa}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\left(\frac{\gamma - 1}{2}\right) \cdot M^2}$$

$$\frac{T_{02s}}{T_a} := \left(\frac{p_{02s}}{p_a}\right)^{\frac{\gamma-1}{\gamma}}$$

$$\frac{T_{02}}{T_a} := 1 + \left(\frac{\gamma - 1}{2}\right) \cdot M^2$$

Stagnation Pressure Ratio

$$r_d := \frac{p_{02}}{p_{0a}}$$

$$\frac{p_{02}}{p_a} := \frac{p_{02}}{p_{0a}} \cdot \frac{p_{0a}}{p_a}$$

$$\frac{p_{02}}{p_a} := \frac{p_{02}}{p_{0a}} \cdot \left(1 + \frac{\gamma - 1}{2} \cdot M^2\right)^{\frac{\gamma-1}{\gamma}}$$

$$\eta_d := \frac{\left(1 + \frac{\gamma - 1}{2} \cdot M^2\right) \cdot \left(r_d\right)^{\frac{\gamma-1}{\gamma}} - 1}{\left(\frac{\gamma - 1}{2}\right) \cdot M^2}$$

Supersonic Inlets

- Flow leaving inlet system must be subonic
- Fully supersonic stream would cause excessive shock losses in compressor
- Mach number for flow approaching subsonic compressor: M_{max}=0.4-0.6

Mach Number Limits

- $4<M<6$
- approaching a subsonic compressor

RAMJET

- No Mach # limitations for RAMJET
- SCRAMJET – supersonic combustion ramjet
- However, no application to date in flight vehicle
- Causes excessive aerodynamic loss

Supersonic Inlets

- The Starting Problem
- The Shock-Boundary Layer Problem
- Flow Stability Problem

The Starting Problem

- Internal supersonic deceleration in a converging passage of nonporous walls is hard to establish
- Current solution-overspeeding the inlet air or varying the diffuser geometry

The Shock-Boundary Layer Problem

- Wall boundary layer may cause strong shocks
- A disastrous effect on duct flow
- Large shocks may require 10 duct widths or more to return to uniform flow

Current solutions

- – Oblique shock - produces less pressure rise
- – Create shock near thinnest part of boundary layer

Flow Stability Problem

- Subcritical-spilling of flow and normal shock upstream of inlet
- Critical-differs only in the amount of spillage
- Supercritical-normal shock occurs at a higher Mach #

Supersonic Diffusers

- Different geometries under testing
- However, diverters create additional drag

Other Considerations

- Shorten inlet lengths-reduce flow separation
- Vortex generators-energize boundary layer

Passive Boundary Layer Control Devices

- Reduce flow distortion by redistributing energy
- But performance of control devices not uniform over entire area
- Need large number of devices to achieve uniform performance

Proposed Active Boundary-Layer Control Scheme

- Use supersonic microjets to reduce distortion over large parametric range
- Grid of supersonic microjets installed in ramp
- Microjets placed at curve of ramp where separation is assumed

Monitor Flow Control

- Mean and unsteady surface flow properties are monitored near boundary layer separation
- Unsteady surface pressures measured with high frequency miiature pressure transducers
- Visualization techniques

Analysis

- Mean, total pressure contours obtained in cross planes at selected streamwise locations
- Contours represent effect of microjets on steady-state distortion and total pressure recovery
- Measure pressure fluctuations above ramp to characterize dynamic distortion

Initial Tests

- Subsonic wind tunnel
- Initial tests will later be used to develop supersonic tests

References

- ***Active Control of Boundary-Layer Separation & Flow Distortation in adverse Pressure Gradient Flows via Supersonic Microjets***, proposal to NASA Langley Research Center, Farrukh Alvi
- http://www.desktopaero.com/appliedaero/blayers/blayers.html
- http://www.aircraftenginedesign.com/abefs.html
- Alvi, Elavarasan, Shih, Garg, and Krothapalli, "Active control of Supersonic Impingin Jets using Micro Jets, AIAA 2000-2236, submitted to AIAA Journal

Calculate the diffuser efficiency in terms of the Mach Number

$$\eta d := \frac{ho2s - ha}{hoa - ha}$$