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

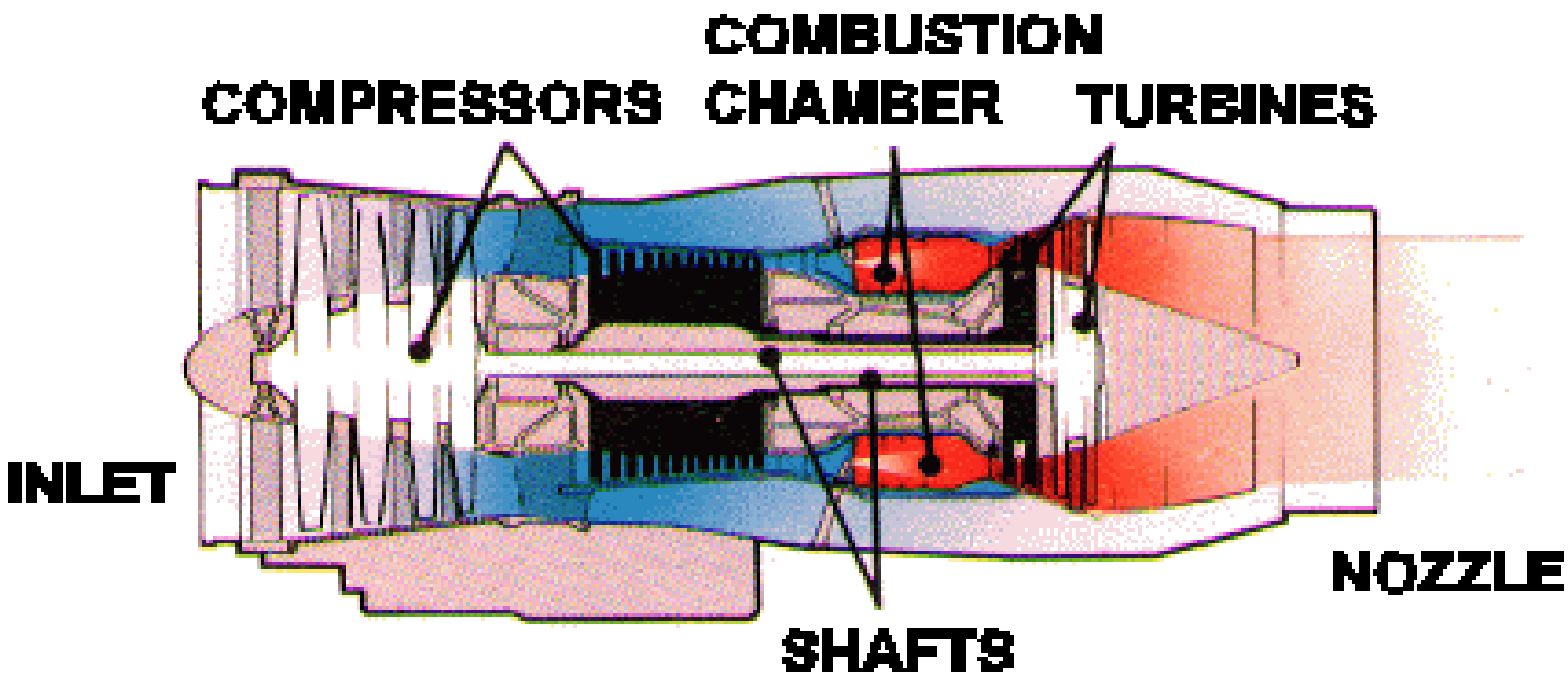
Design Objectives

- 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



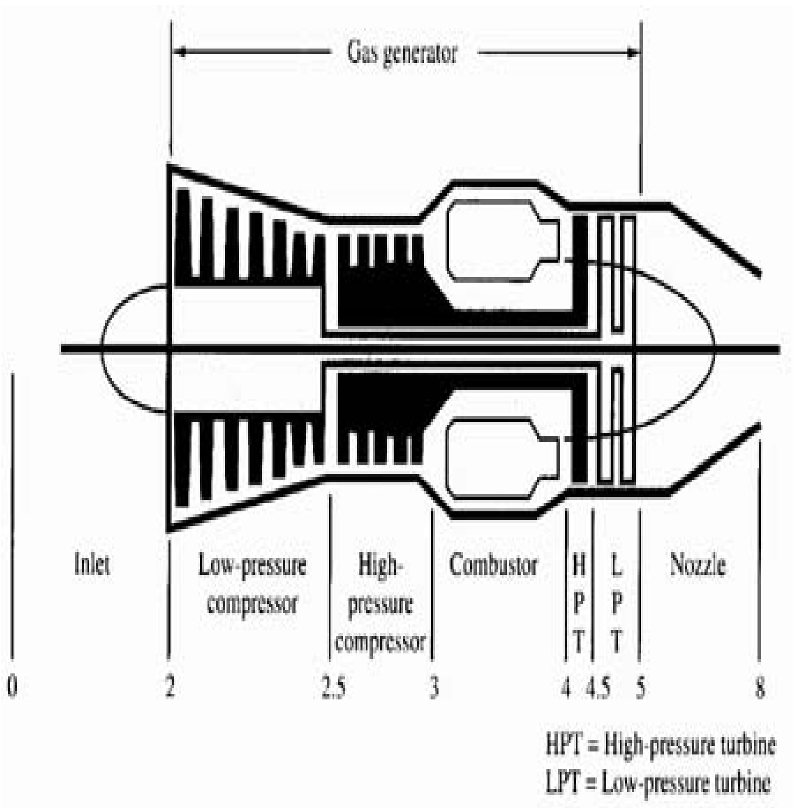
Inlet

- 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

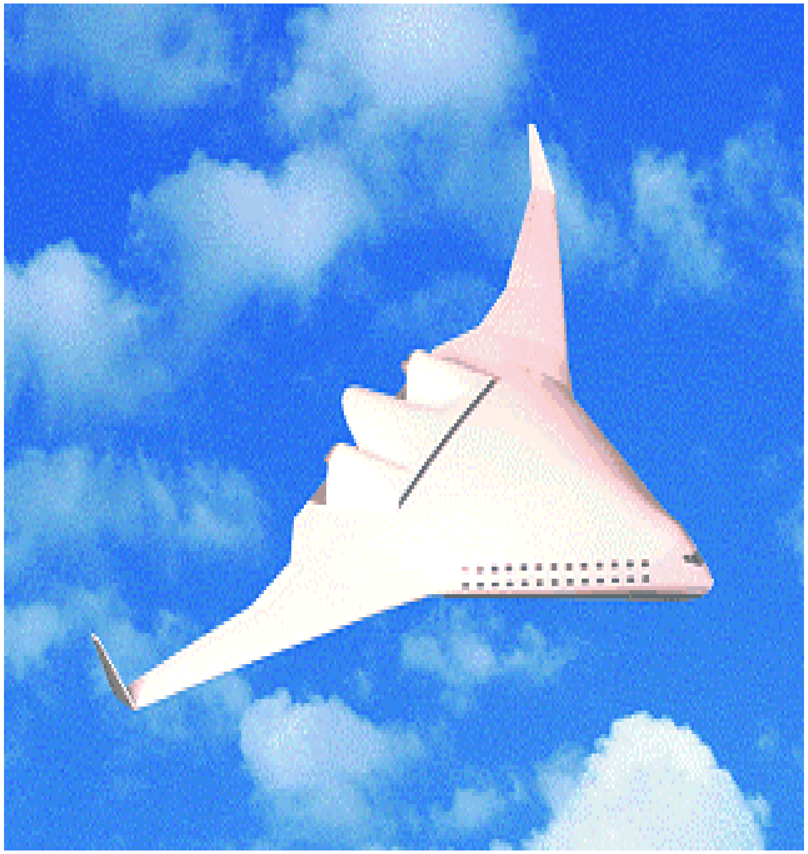
- Pressure and/or velocity flow distortions at engine (compressor) fanface can compromise engine efficiency.
- Separation of incoming boundary-layer flow can reduce pressure recovery and lead to:
  - Unsteady loading
  - Increased fatigue of engine fan blades
  - Aerodynamic stall on compressor blades[1]

Integrated Propulsion Systems

- Joint Strike Fighter
- NASA/Boeing, Blended Wing Body

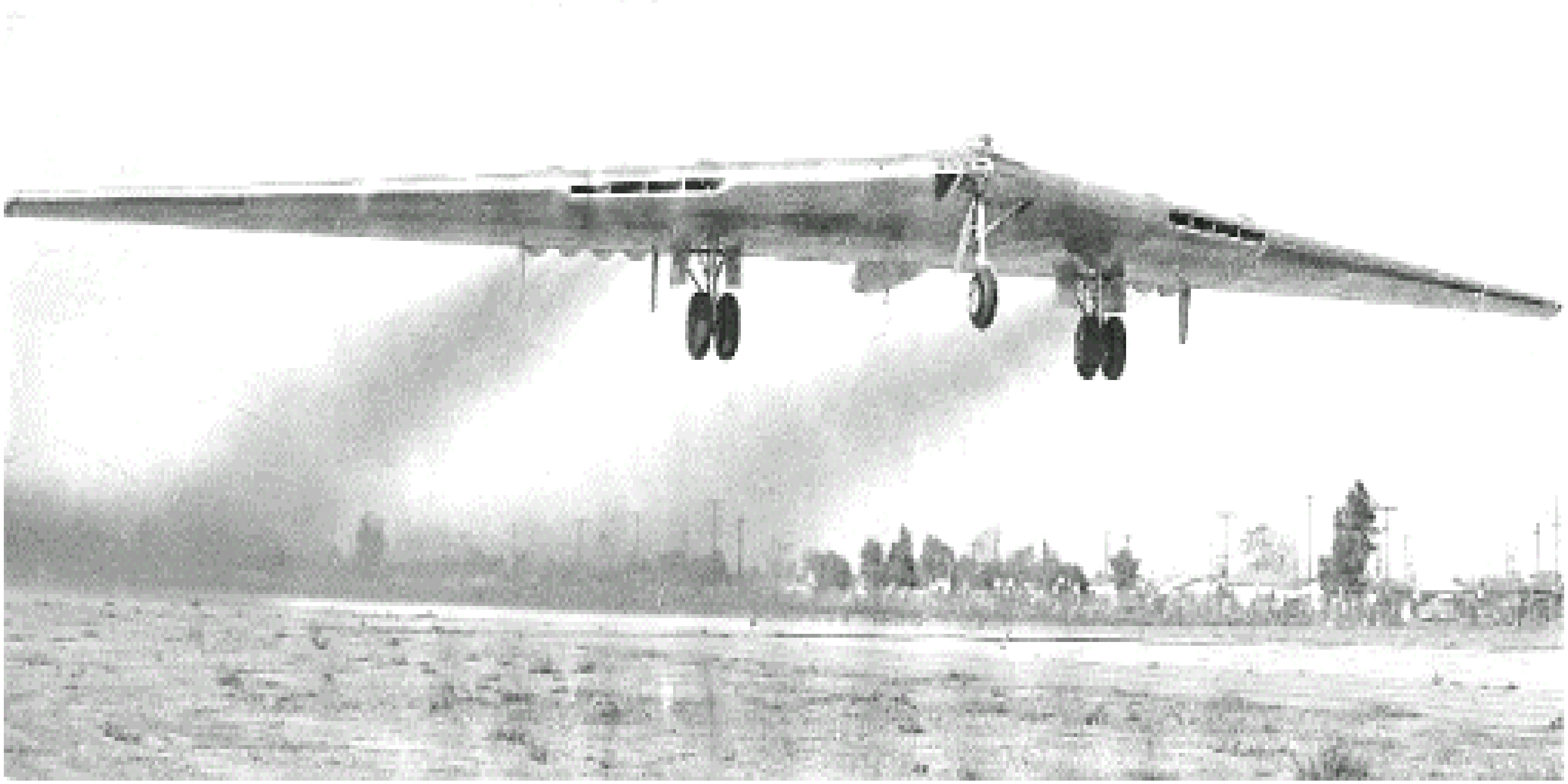
Boeing JSF X-32B
Joint Strike Fighter

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

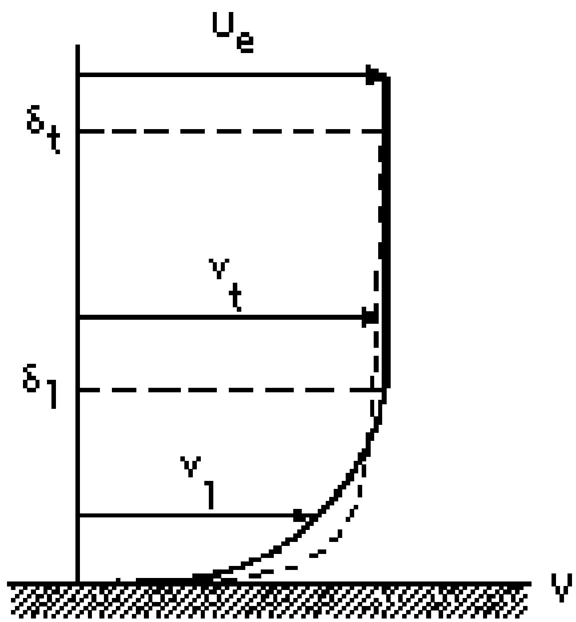
Boundary Layer Separation must be Avoided

- 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



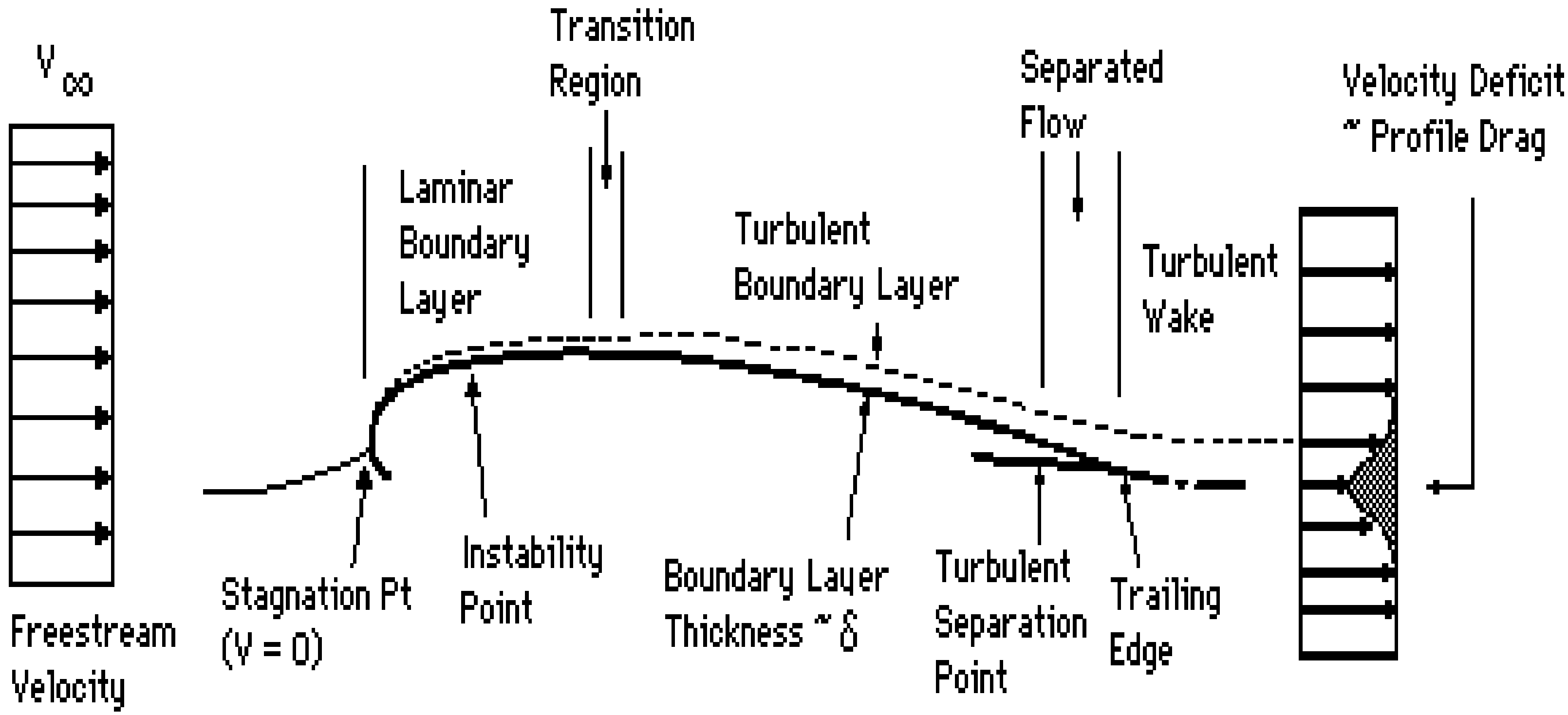
Boundary layer velocity profiles

——— Laminar

- - - - Turbulent

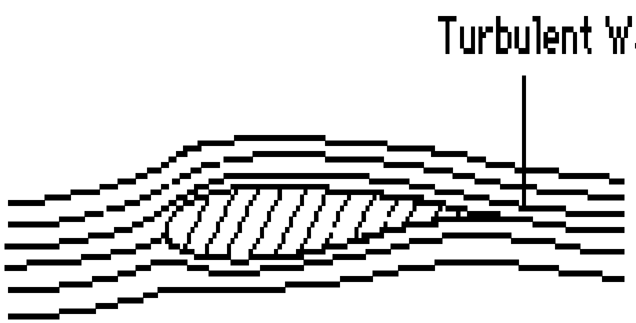
- [2]Boundary layers occur on surface of bodies in viscous flow

Laminar Boundary Layer

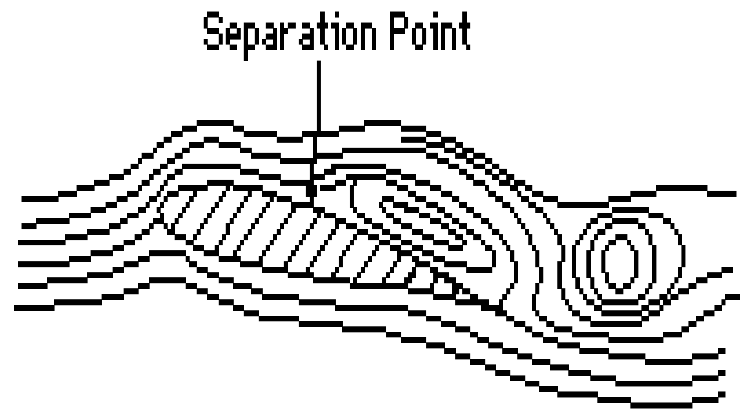


Thickness of boundary layer increases downstream

Viscosity causes boundary layer separation



Attached Flow
Low Angle of Attack



Massive Flow Separation
High Angle of Attack

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

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