Jet and Rocket Propulsion

AE4451

LECTURE 30

Sedina Tsikata – March 27, 2023

Overview

- what we saw in Lecture 29
    - electric propulsion: systems and principles of operation (cont'd)
    - analysis of turbine engine components
        - inlet/diffuser (subsonic)

- today
    - analysis of turbine engine components
        - inlet/diffuser (supersonic)

Supersonic inlet design

Inlet features

- flow requirements
  - slow initial supersonic flow to subsonic speeds; needed for combustion (except for scramjets)

- design goals
  - produce desired Mach number at exit
  - provide required mass flow rate across engine (thrust requirement)
  - minimize stagnation pressure loss
  - ensure stable operation
    - i.e. avoid drastic inlet property changes for small flight condition changes

Supersonic inlet design

Inlet classifications

- classification often made according to location of supersonic wave compression system
    1. internal compression
    2. external compression
    3. mixed compression

- an alternate classification according to geometry
    1. two-dimensional (rectangular)
        - advantage of design simplicity, variability in inlet flow
    2. axisymmetric (circular)
        - slight advantage over rectangular: weight, pressure ratio

heritageconcorde.com

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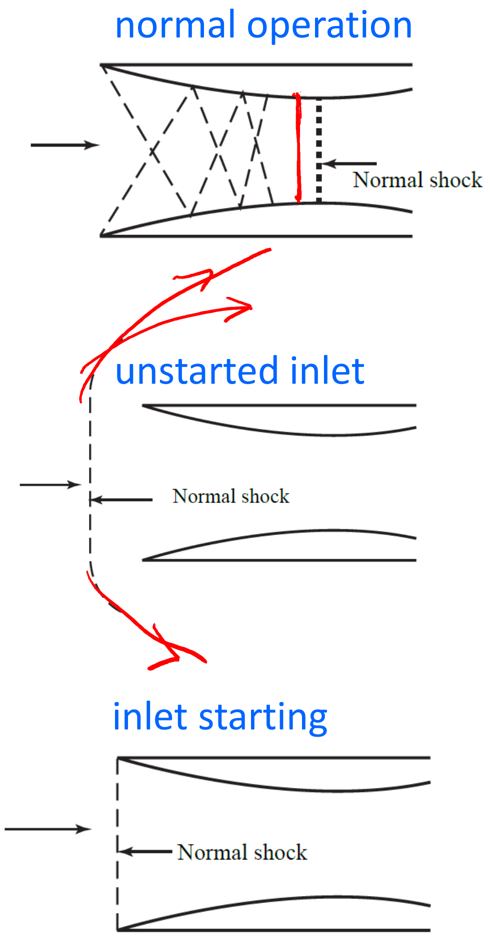
Supersonic inlet design

Internal compression inlet



- series of internal oblique shock waves
- terminal normal shock is downstream of throat (stable position)

- can occur if terminal shock pushed to throat (unstable position); any conditions which make inlet no longer correctly sized to absorb normal shock
- internal flow pattern disrupted, resulting in inlet "unstarting"
- normal shock forms ahead of inlet
- as a result: low total pressure ratio (about 0.52), reduced mass flow through the inlet, high spillage drag, and possible engine flameout

- restart inlet by increasing throat area so that shock touches inlet (critical operation)

Mattingly

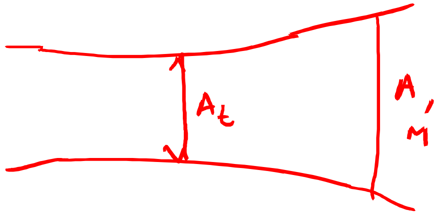
Supersonic inlet design

Area ratio

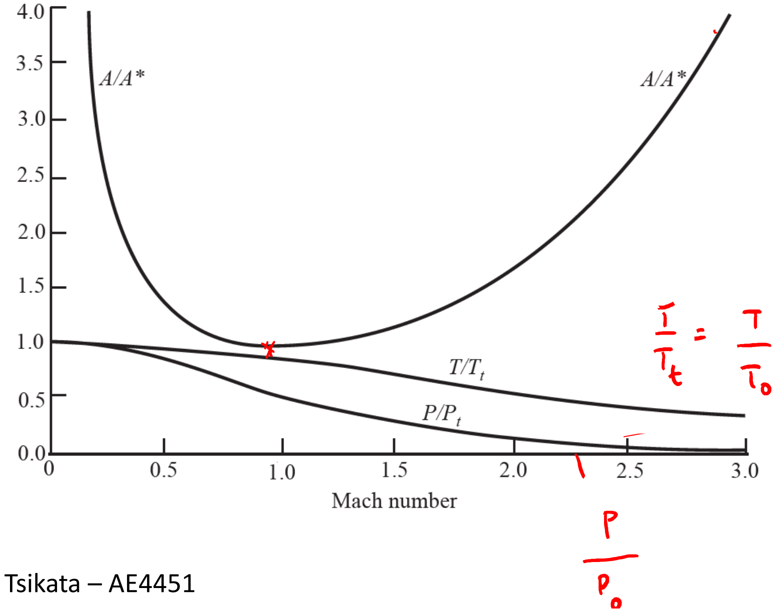
- still using isentropic assumptions, can write relationship between throat area and any section area

$$\frac{A}{A^*} = \frac{1}{M}\left[\frac{2}{\gamma+1}\left(1+\frac{\gamma-1}{2}M^2\right)\right]^{\frac{\gamma+1}{2(\gamma-1)}}$$

* = sonic conditions at throat
M = Mach number at some point in duct



- recall isentropic assumption allows pressure and temperature ratio to be written in terms of M



$\frac{T}{T_t} = \frac{T}{T_o}$

$\frac{P}{P_o}$

Mattingly

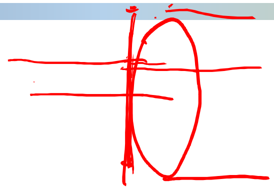
$$\frac{p_o}{p} = \left(1 + \frac{\gamma-1}{2}M^2\right)^{\frac{\gamma}{\gamma-1}} \qquad \frac{T_o}{T} = 1 + \frac{\gamma-1}{2}M^2$$

- large variation in area ratio needed: need to account for this in design

Supersonic inlet design

External compression inlet

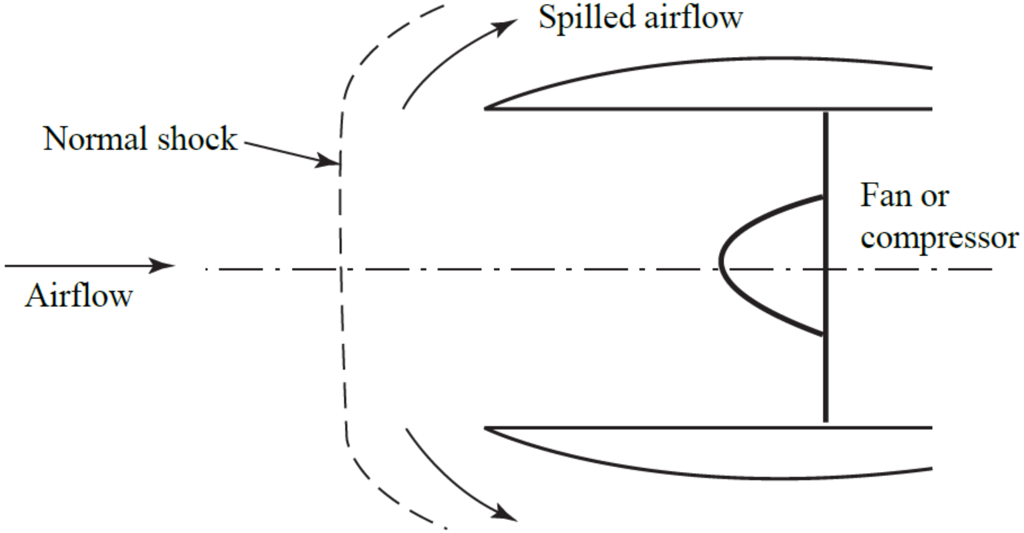
- Pitot inlet/normal shock inlet



- achieves compression through single normal shock

- total pressure recovery = pressure ratio across normal shock η_r

- efficient pressure recovery up to M = 1.6



Supersonic inlet design

Pitot inlet

- subsonic aviation: rigid annular Pitot inlet
  - rigid geometry implies tradeoff

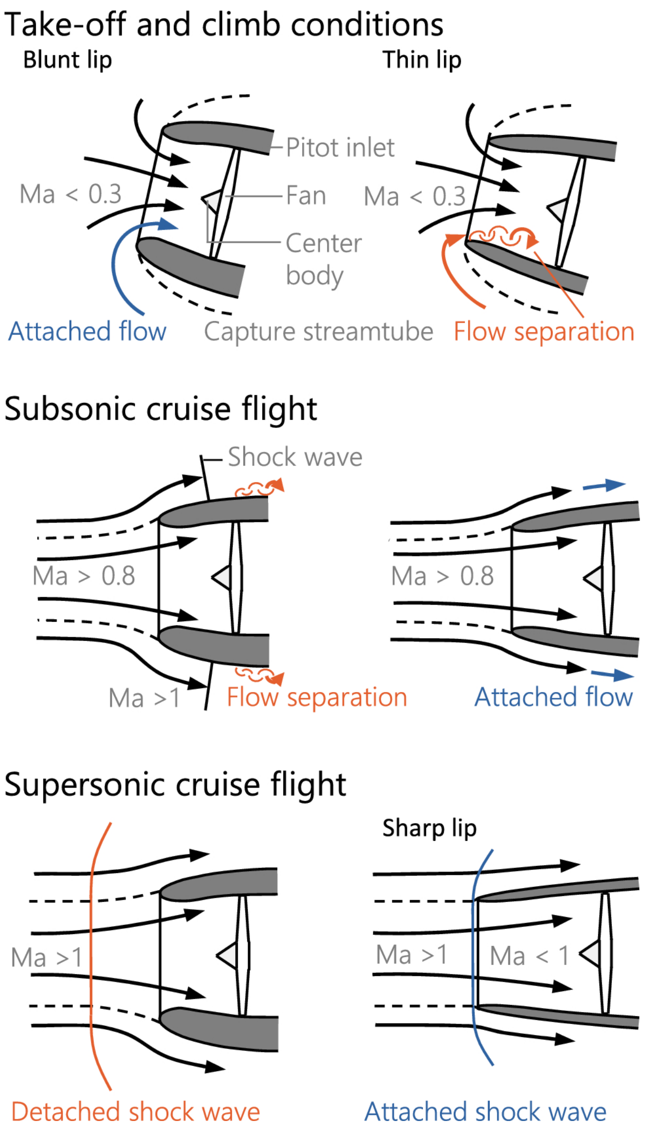
take-off and climb:

- avoid flow separation using rounded thick geometry

cruise:

- minimize aerodynamic drag using thin geometry

- supersonic aviation: thin, sharp geometry preferred



Kazula and Höschler, CEAS Aeronautical Journal 2021

Supersonic inlet design

Pitot inlet – variable geometry

example: MorphElle project
(morphing enabling technologies for propulsion system nacelles)

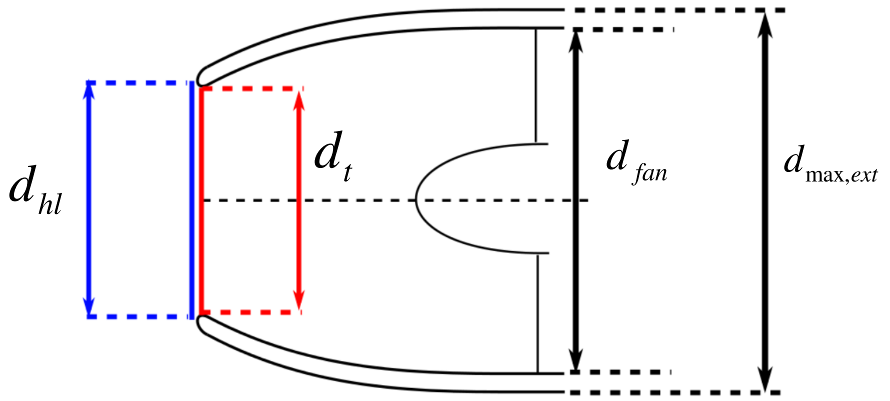
- advantages
  - adaptability for various stages of flight

- disadvantages
  - complexity: special materials, e.g. elastic
  - might increase manufacturing cost, mass
  - more possible failure modes, safety-critical events
  - increased maintenance, shorter service life

not currently used in subsonic aviation

strategies can involve varying:

- curvature of the inlet lip
- cross-sectional areas at inlet entry and throat level
- lengths of inlet lip, diffuser, and nacelle forebody
- curvature of the nacelle forebody



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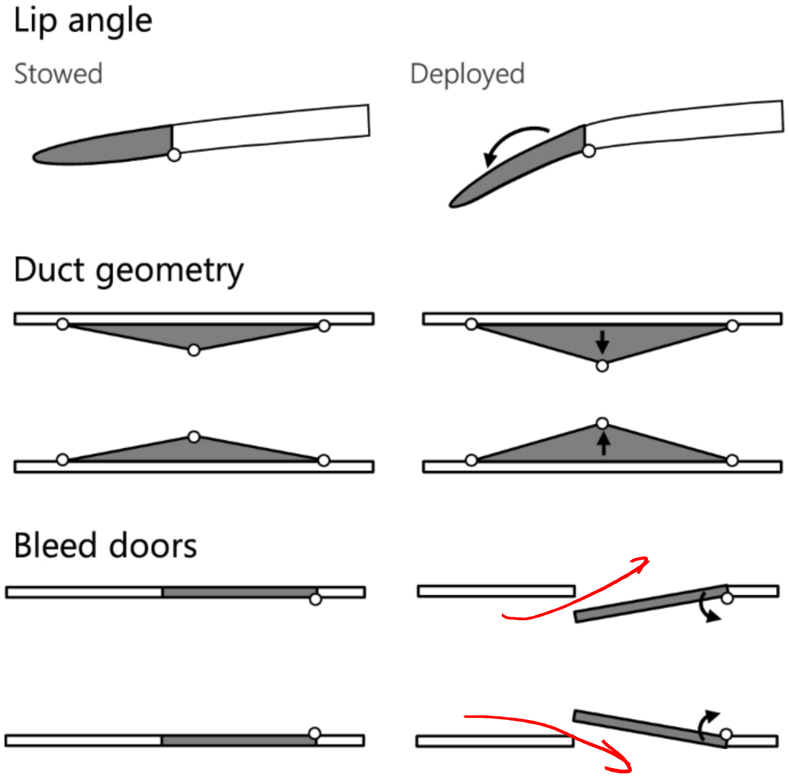
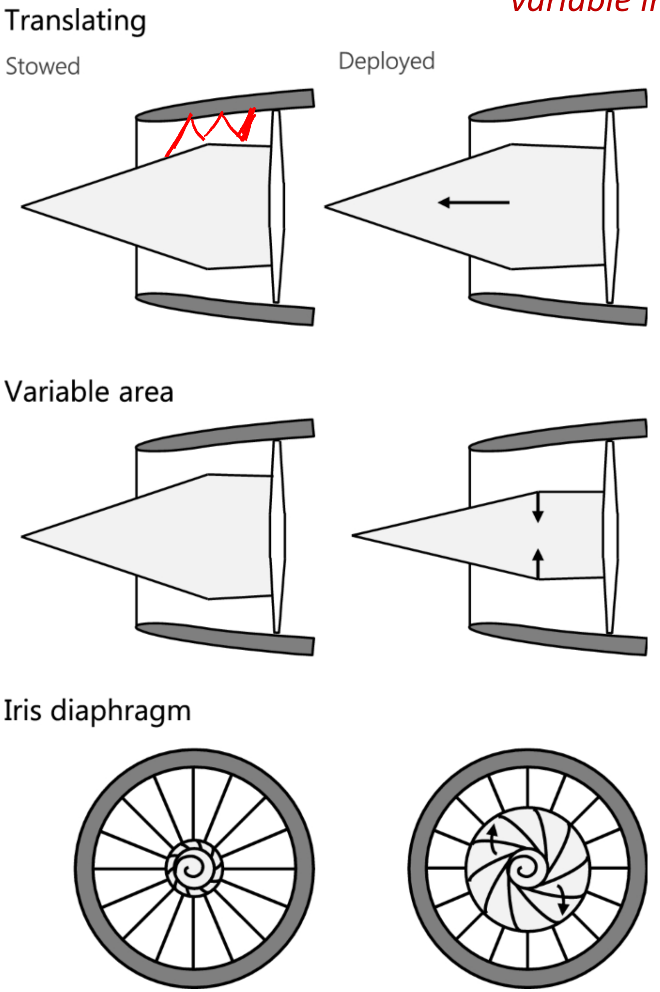
Supersonic inlet design

Variable geometry



variable rectangular inlet cowls

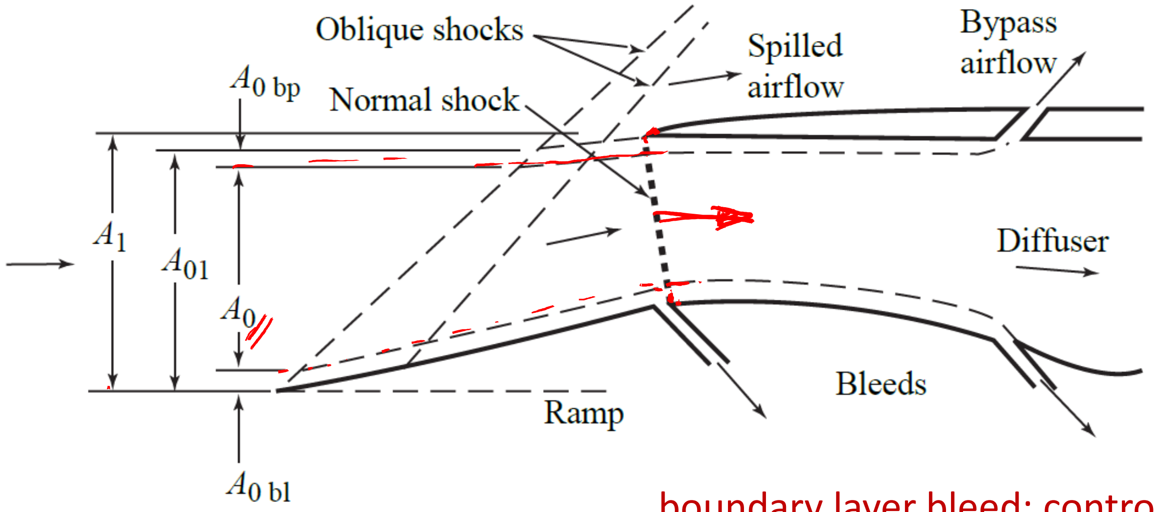
variable inlet center body



Kazula and Höschler,
CEAS Aeronautical Journal
2021

Supersonic inlet design

External compression inlet with multiple oblique shocks



Mattingly

boundary layer bleed: control flow separation, limit pressure loss, stabilize shock

- uses series of oblique shocks to increase pressure recovery
- follow with subsonic diffuser duct to turn flow back to axial direction

- aim for critical operation: normal shock at, or very near to, cowl lip
  - here, inlet is said to be matched to the engine
  - minimizes fraction of air spilled around inlet

A_1 = inlet flow area

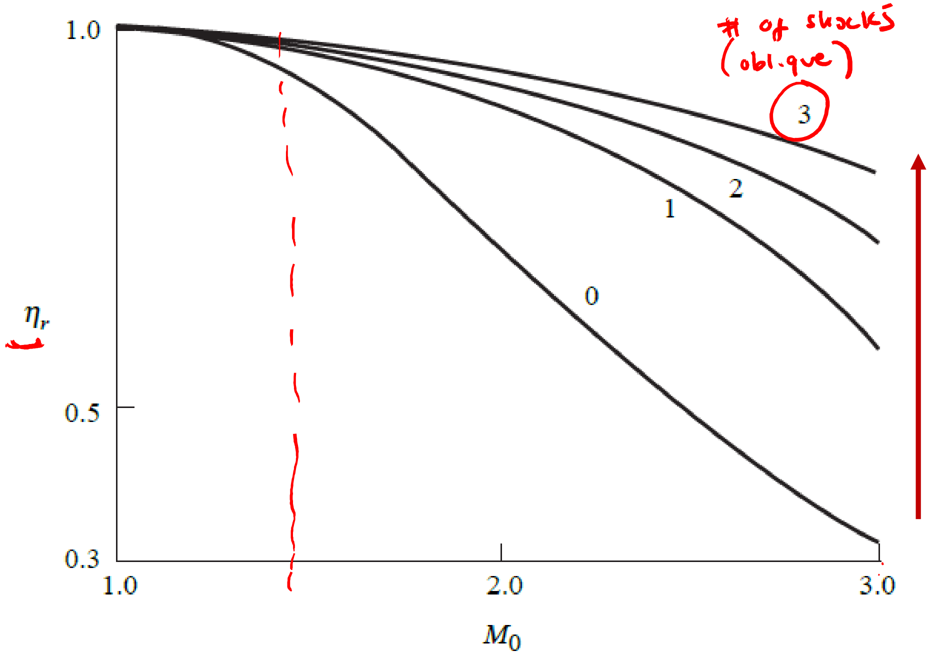
A_0 = engine flow area

$A_{0,bp}$ = free stream tube area with bypass flow

$A_{0,bl}$ = free stream tube area with boundary-layer bleed

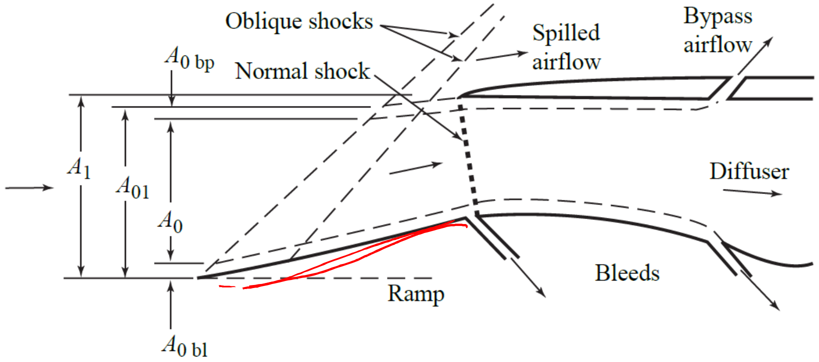
Supersonic inlet design

External compression inlet with multiple oblique shocks



Mattingly

- larger number of oblique shocks, increases pressure ratio η_r
- notice importance of effect at higher freestream M_0
- at higher freestream M, turn flow through increasingly larger angles in ramp section:
  - increased cowl angle, cowl drag
- efficient for M up to 2.5
  i.e. balance between pressure ratio and cowl drag

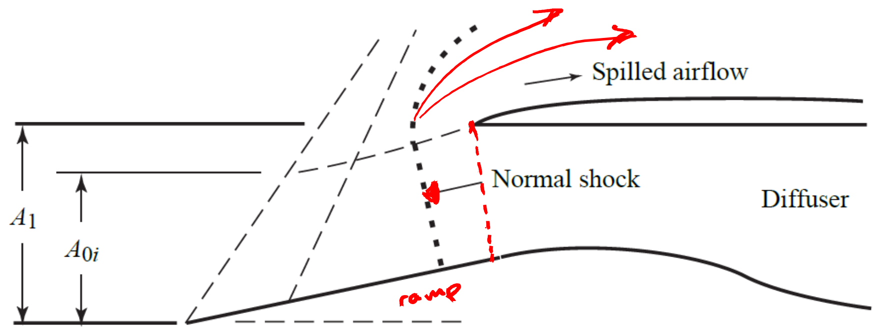


Supersonic inlet design

Subcritical and supercritical operation of external compression inlet

- if the flow is not matched to the engine, we have two possible scenarios

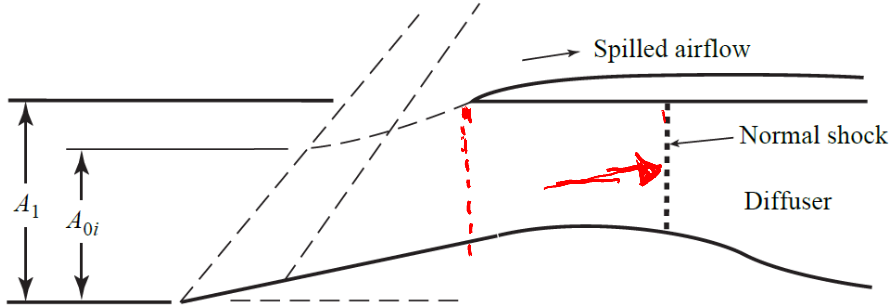
subcritical inlet operation



subcritical inlet operation

- terminal normal shock moves upstream
- spilled air increases
- increase in spillage drag

supercritical inlet operation



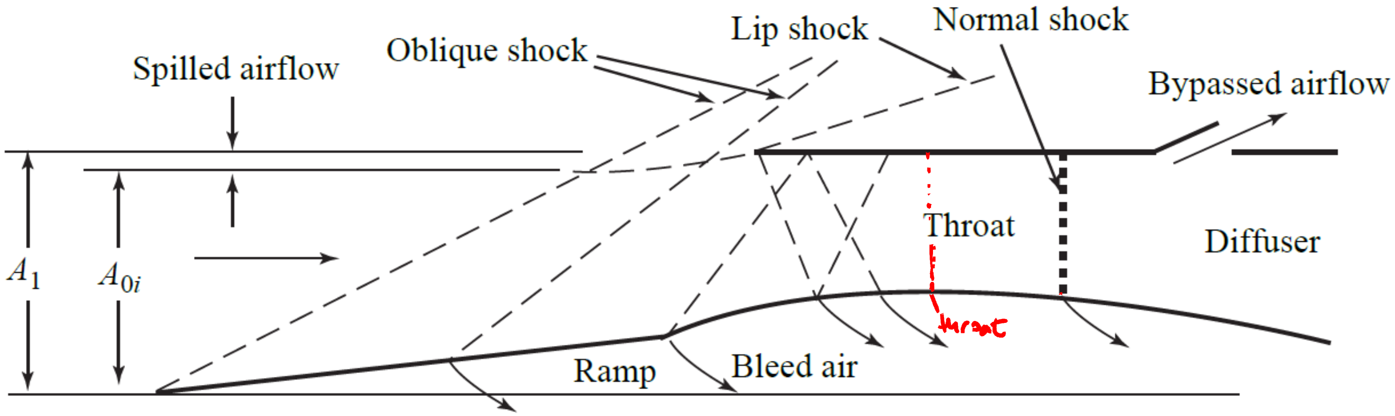
Mattingly

supercritical inlet operation

- terminal normal shock sucked downstream into diffuser
- strengthens shock
- lower inlet total pressure recovery, reduced performance

Supersonic inlet design

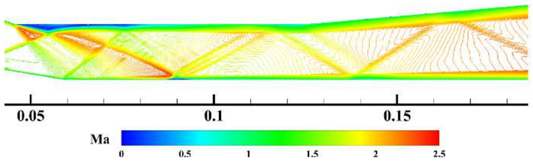
Mixed compression inlet



Mattingly

(a) Experimental schlieren picture

(b) Numerical schlieren contour



(c) Numerical Mach contour

Liu et al, Appl. Phys 2021
2D supersonic inlet

- more complex, heavier, costlier design than external compression inlet
- uses combination of:
  - external oblique shocks
  - internal reflected oblique shocks
  - terminal normal shock

  to produce compression
- optimal position of normal shock = just downstream of inlet throat

Supersonic inlet design

Mixed compression inlet

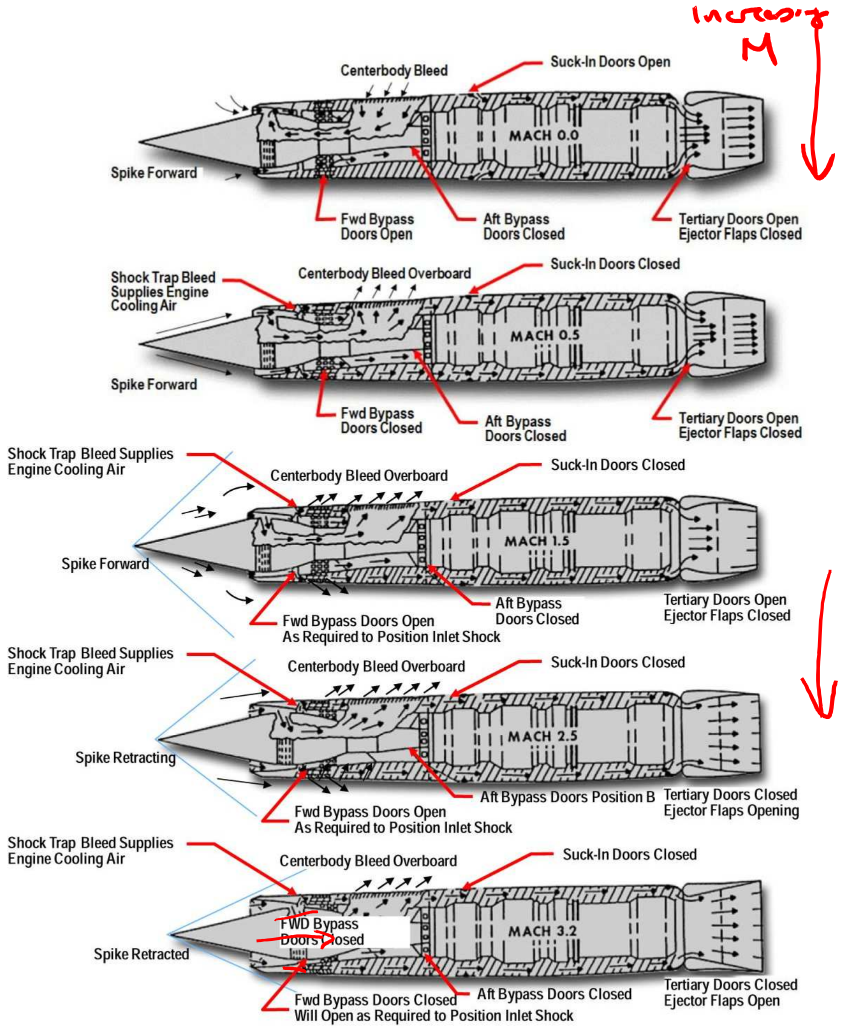
- example: SR-71 Blackbird
  - cruise speed Mach 3.2 (highest manned velocity)
  - variable inlet geometry
  - axi-symmetric mixed compression inlet chosen to:
    - lower weight, drag while providing range, cruise performance, high pressure recovery at Mach 3 and above

Lockheed Martin

Supersonic inlet design

Mixed compression inlet: SR-71

- forward bypass doors: ensure flow continuity
    - area continually varied to prevent unstart, ensure flow uniformity
- aft bypass: enables operation at low speed, power, while avoiding unstart
- inlet bleed (cowl and spike): boundary layer control



enginehistory.org

Supersonic inlet design

Inlet and diffuser pressure recovery

- inlet total pressure ratio

$$\tau_d = 1 \text{ (adiabatic)}$$

$$\pi_d = \frac{\text{total pressure exiting inlet}}{\text{total pressure entering inlet}}$$

< 1 due to friction and shock losses

- inlet total pressure ratio

$$\pi_d = \underbrace{\pi_{d\max}}_{\text{pressure loss due to friction}}\underbrace{\eta_r}_{\text{pressure loss due to ram recovery (caused by shocks)}}$$

the inlet’s overall pressure ratio is the product of the
the diffuser pressure ratio and ram pressure ratio

- inlet *ideal* total pressure ratio = total pressure recovery η_r

Supersonic inlet design

Relationship between pressure ratio and pressure recovery

- inlet ideal total pressure ratio = total pressure recovery η_r

$$\eta_r = \begin{cases} 1 & M_0 \le 1 \\ 1 - 0.075(M_0 - 1)^{1.35} & 1 < M_0 < 5 \\ \dfrac{800}{M_0^{\,4} + 935} & M_0 > 5 \end{cases}$$

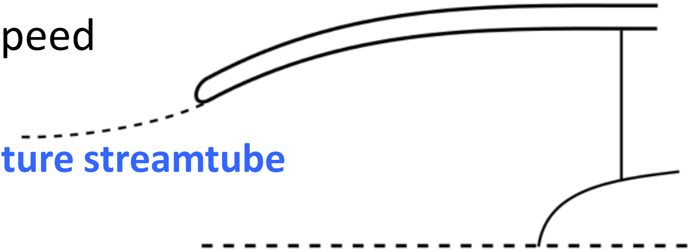
MIL-E-5008B specification

- total pressure recovery of the inlet = product of the total pressure ratio across each shock

Supersonic inlet design

Mass flow considerations

- subsonic case: we previously saw streamline patterns based on flow speed
  - notion of a streamtube



- mass flow characteristics are also important in the supersonic case

$$\frac{\dot{m}_i}{\dot{m}_1} = \frac{\text{actual mass flow rate at inlet } \mathrm{m_i}}{\text{mass flow rate which could be captured by inlet } \mathrm{m_1}} \qquad \Rightarrow \frac{\dot{m}_i}{\dot{m}_1} = \frac{\rho v A_i}{\rho v A_1}$$

i.e. **inlet mass flow ratio** = inlet area ratio

- engine mass flow ratio defined as

$$\frac{\dot{m}_0}{\dot{m}_1} = \frac{\text{required engine mass flow rate } \mathrm{m_0}}{\text{mass flow rate which could be captured by inlet } \mathrm{m_1}}$$

$$\Rightarrow \frac{\dot{m}_0}{\dot{m}_1} = \frac{A_0}{A_1}$$

can be written in terms of corrected mass flow

Supersonic inlet design

Mass flow considerations

- the engine mass flow ratio can also be written in terms of the corrected mass flow

$$\frac{\dot{m}_0}{\dot{m}_1} = \frac{\dot{m}_{c0}}{\dot{m}_{c1}} \pi_d$$

$\dot{m}_{c0}$ = corrected engine mass flow rate
$\dot{m}_{c1}$ = corrected mass flow rate based on capture area
π_d = inlet total pressure ratio

recall: we imposed a condition at the throat of a subsonic inlet from which we could derive a corrected maximum mass flow rate

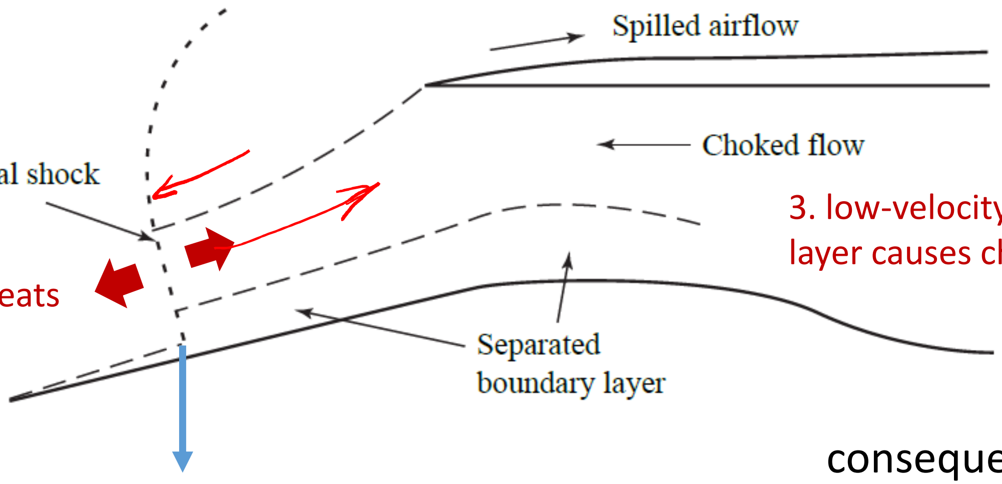
$$M < 0.8$$

Supersonic inlet design

Supersonic flow phenomena: “buzz”

- low frequency, high amplitude pressure oscillation

4. shock pulled up ramp where boundary layer thins; unchoked flow condition restored and mass flow rate increases again



5. shock retreats

3. low-velocity flow of separated layer causes choking

in subcritical regime:

1. normal shock meets boundary layer on wall
2. boundary layer separates

consequences:

- possible engine unstart
- possible engine flameout (combustion extinction)