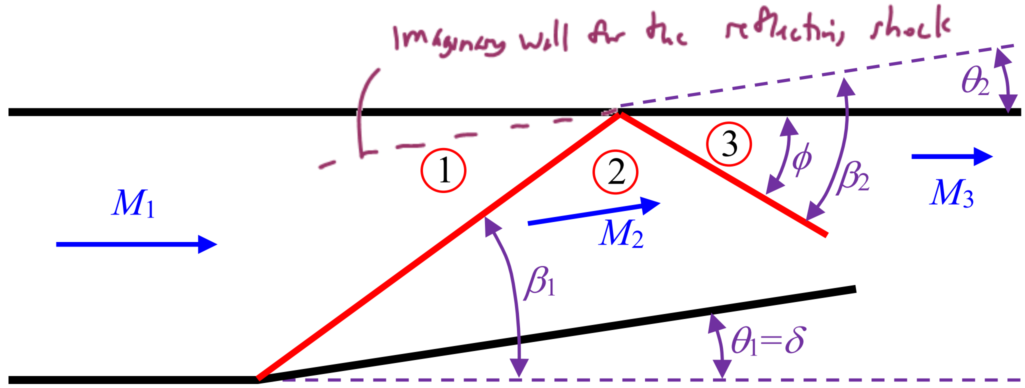
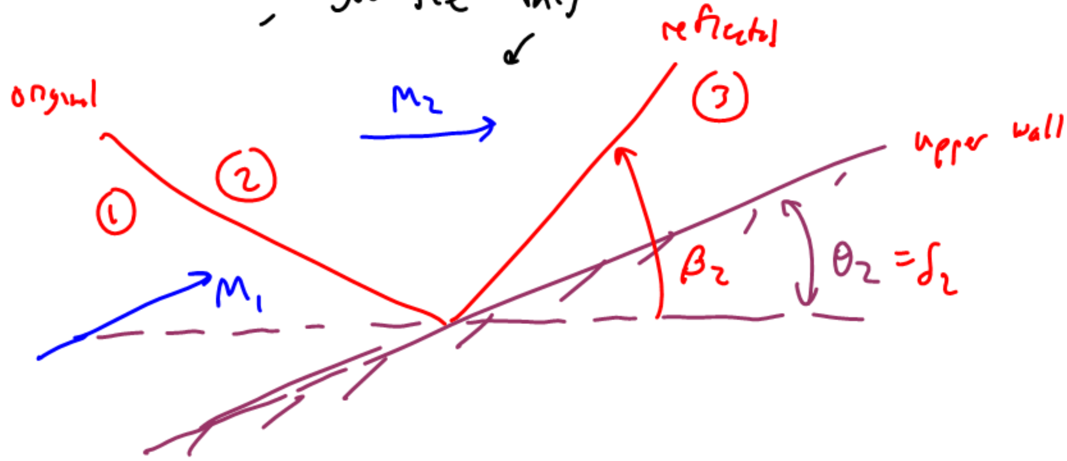
Today, we will:

- Finish oblique shocks: procedure for oblique shock reflection calculations and do an example problem
- Discuss a practical application of oblique shocks – supersonic engine inlets
- Begin to discuss Prandtl-Meyer (P-M) expansion fans in 2-D compressible flows
- If time, give some brief histories about Prandtl and Meyer

Oblique shock reflection from a wall (continued):



When turn this upside down & tilt so that M_2 is parallel to the floor, you see this



KEY → $\theta_2 = \theta_1 = \delta_2$ because the initial walls are parallel

- ② to ③ is the same as ① to ② (same eqs, etc.) but at a different Mach #

PROCEDURE TO GET M_3, P_3, T_3, etc.

SAME AS BEFORE (ONE OBLIQUE SHOCK)

1) Calc β_1 for given M_1, θ_1 $(\theta_1 = \delta_1)$ from θ-β-M eq. (implicitly)

2) Calc $M_{1,n} = M_1 \sin\beta_1$

& calculate $M_{2,n}$ across a "normal" shock using $M_{1,n}$

$$M_2 = \frac{M_{2,n}}{\sin(\beta_1 - \theta_1)}$$

3) Calculate $\frac{P_2}{P_1}$, $\frac{T_2}{T_1}$, etc from normal shock eqs but use $M_{1,n}$ & $M_{2,n}$

REPEAT STEPS 1) to 7) FOR THE REFLECTING SHOCK

USE 2 in place of 1
3 in place of 2

4) Use M_2 & θ_2 to calc β_2 (θ-β-m eq)

(Here $\theta_2 = \theta_1$)

5) Calc $M_{2,n} = M_2 \sin\beta_2$ — Get $M_{3,n}$ across "normal" shock

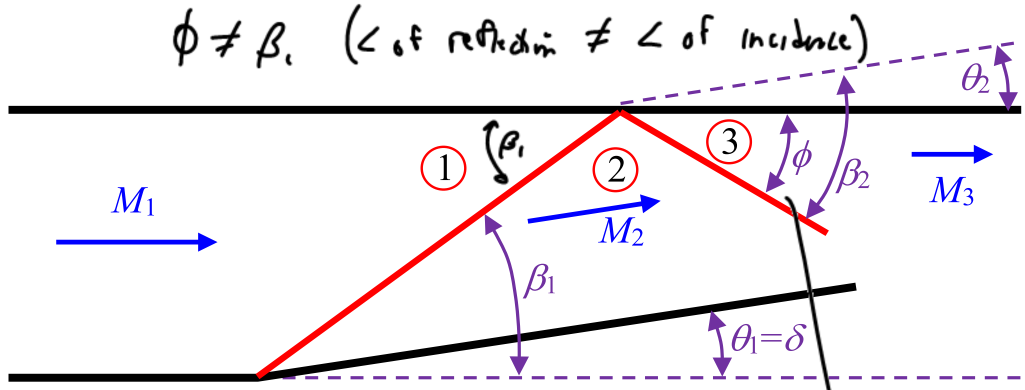
$$M_3 = \frac{M_{3,n}}{\sin(\beta_2 - \theta_2)}$$

6) Calc $\frac{P_3}{P_2}$, $\frac{T_3}{T_2}$, etc

7) Calc $P_3 = \frac{P_3}{P_2}\frac{P_2}{P_1}P_1$ Similarly for T_3, ρ_3

Example: Converging nozzle flow

Given: Air flows steadily in a rectangular duct with a sudden contraction at the bottom as sketched.



The duct is insulated and we ignore friction. We measure:

- $M_1 = 2.8$
- $T_1 = 288$ K
- $P_1 = 101.325$ kPa
- $\delta = 16°$

$\phi = \beta_2 - \theta_2$

To do: Calculate β_1, β_2, M_2, T_2, P_2, M_3, T_3, P_3, and ϕ.

Solution:

Assumptions and Approximations:

1. The air is an ideal gas with constant properties.
2. Friction along the duct walls is negligible.
3. The flow is adiabatic.
4. Both oblique shocks are weak oblique shocks.

I followed the above procedure. *Students are strongly encouraged to use these numbers as a test case before doing the homework problem*. You should get the same answers as these:

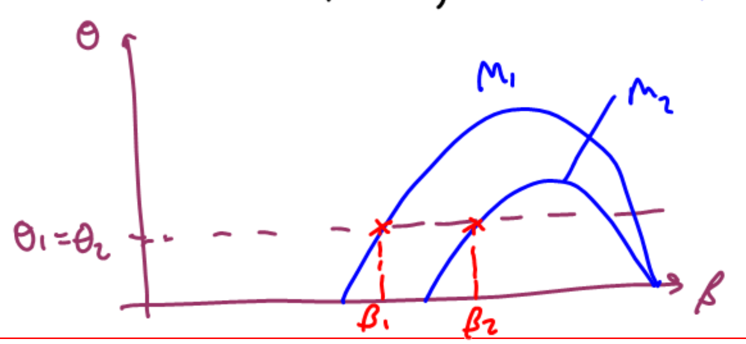
Answers:

$\beta_1 = 34.9°$, $\beta_2 = 45.3°$, $\phi = 29.3°$
$M_2 = 2.059$, $T_2 = 400.3$ K, $P_2 = 286.8$ kPa
$M_3 = 1.458$, $T_3 = 519.0$ K, $P_3 = 669.5$ kPa

Comments: · $\phi \neq \beta$ (reflection is not specular) $M_1 > M_2$

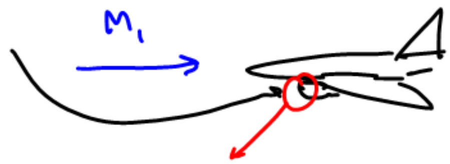
· $\beta_2 > \beta_1$

· $M_1 > M_2 > M_3$



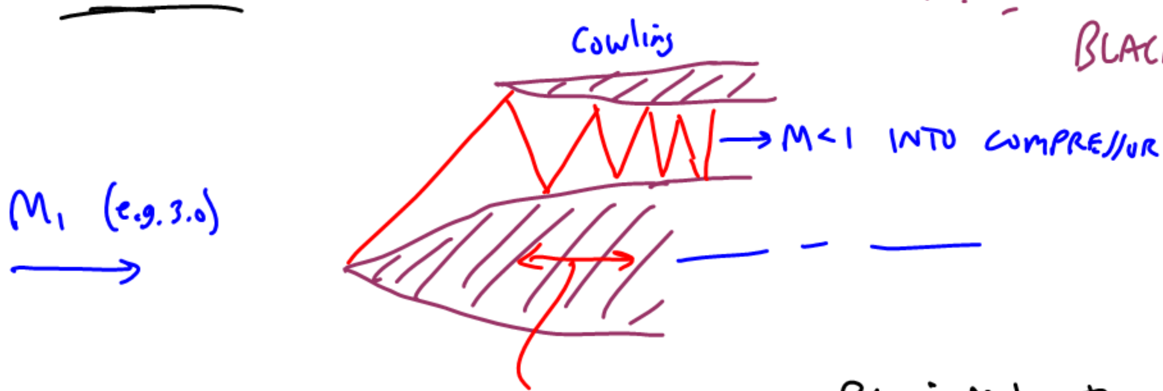
APPLICATIONS OF OBLIQUE SHOCKS

- AT JET ENGINE INLETS



- **Round inlets** — use a centerbody

E.G. SR-71 BLACKBIRD

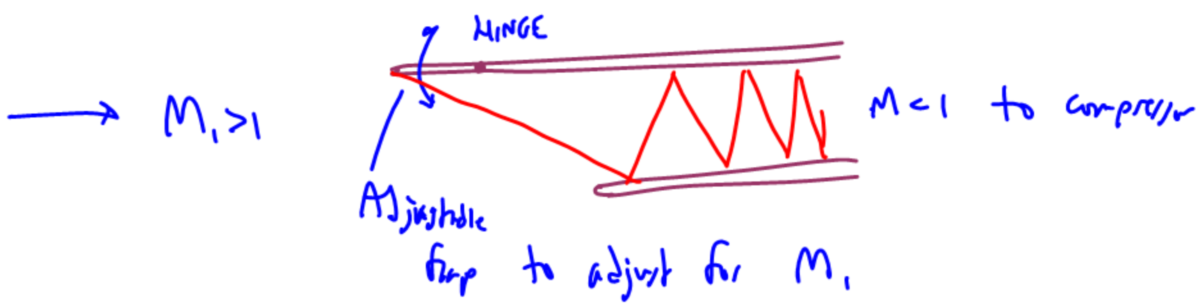


Slides forward & backward to adjust for M_1

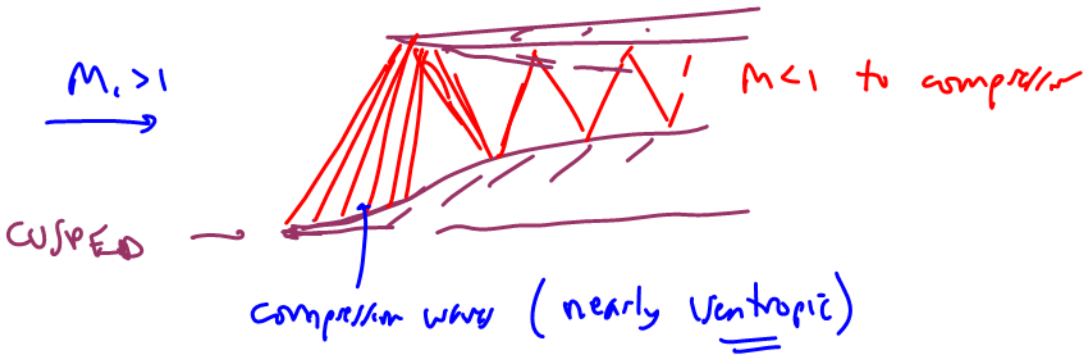
$P\uparrow$ & $M\downarrow$ through each successive oblique shock

This is a significant pressure rise contribution for the total compression

- **Rectangular Inlets** Eg. F-15



• **CURVED "RAMPED" INLET** E.g. Concorde

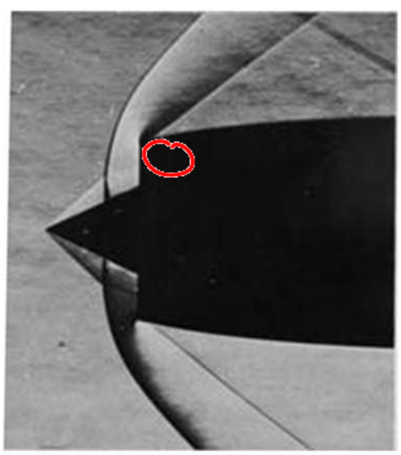


EFFICIENT DUE TO COMPRESSION WAVES!

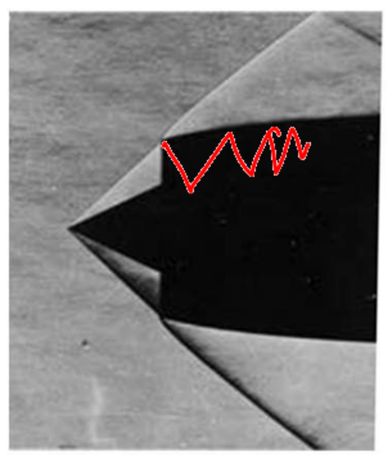
Examples of supersonic engine inlets:

SR-71 Blackbird: Round inlets with center cones ("spike inlets").

Note: If the center cone is not at the proper location for the Mach number, a bow shock forms and the engine is "unstarted".



Unstarted inlet

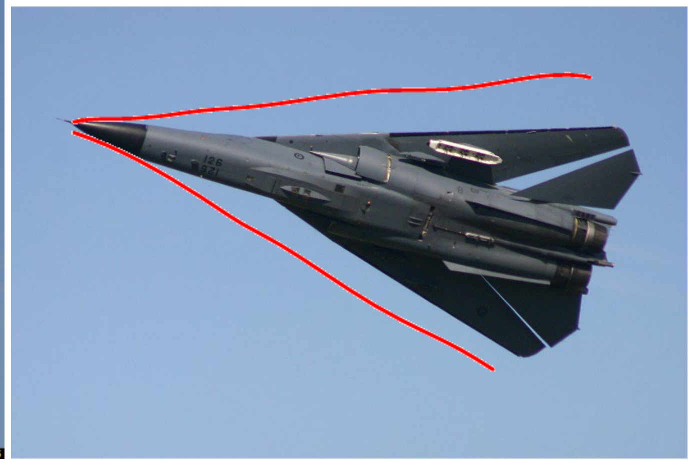


Started Inlet

Schlieren imaging of Supersonic inlet shocks

F-104 Starfighter: Half-round inlets with halfcones.

F-111 Starfighter: Quarter-cone inlets and adjustable wings! (also called armpit inlets).



F-15 Eagle: Rectangular inlets with variable geometry flap, depending on Mach number.

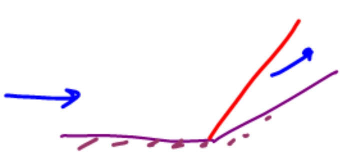
In the picture on the above right, the flap on the left is positioned for subsonic flight, while the flap on the right is positioned for supersonic flight, with multiple oblique shocks and reflected oblique shocks as discussed in class.

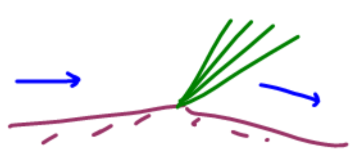
PILOT WINKS AT YOU

F-22 Raptor: Rectangular inlets.

XB-70: Dual rectangular inlets designed for multiple oblique shocks and reflections, designed for Mach 3.0 cruising (1960's)

Concorde: Four engines with rectangular inlets and variable geometry ramps.





EXPANSION FAN (NEXT TIME)