Shock Inlet

1 Overview

For air-breathing engines on supersonic vehicles, we need to **slow down the flow** ($M < 1$) before it enters the engine, and usually also need to ensure subsonic flow leaving inlet. Therefore, we need **supersonic diffuser** in the let.

Besides this, we also want to **minimize the pressure loss**, so we need less fuel burn to get desired thrust. We also need to operate the engine over desired range of flight Mach numbers (M_∞) and meet the thrust requirement. These are all the requirements we need for inlet design.

2 Inlet Options

To slow down the supersonic flow to subsonic, normally we have three ways:

1. Converging-diverging geometry (no shock):

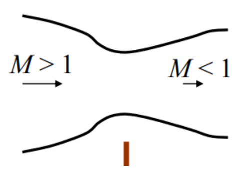

Figure 1: CD Diffuser

2. Normal shock:

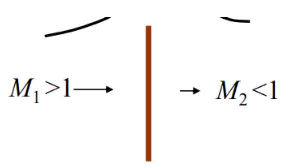

Figure 2: Normal Shock

3. Oblique Shock:

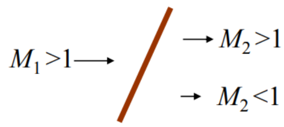

Figure 3: Oblique Shock

2.1 Converging-Diverging Inlet

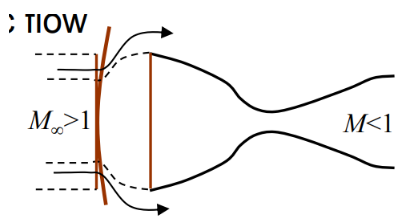

Figure 4: CD Inlet

Theoretically, this method has the **lowest potential pressure loss**, because this is close to isentropic flow. However, this geometry has some technical issues:

1. **Starting problem:** To fulfill the requirements, this geometry need to **swallow shock (let the shock inside the inlet)** , like supersonic wind tunnel. This requires **overspeeding** ($M_\infty > M_{design}$), until **shock sits at entrance**. However, to limit overspeed level usually requires **variable area throat or bypass valves**, which will be heavy and complex.

2. **Stability Problem:** If we could not control the shock well and let shock leaves throat, can cause the lowering mass flow at the engine exit.

Now we analyze a case of overspeeding CD inlet with fixed throat area. The inlet will be choked when:

$$M_{entrance} = M_{subsonic,(A/A^*)_{M_{design}}} \tag{1}$$

Which means the Mach number at the entrance need to be equal to subsonic Mach number calculating by area ratio equation using M_{design}. Therefore we need to increase the flight Mach number until:

$$M_{2,aftershock} = M_{subsonic,(A/A^*)_{M_{design}}} \tag{2}$$

Then the shock will move to inlet. For example, if $M_{design} = 1.7$, then based on the area ratio equation, $A/A^* = 1.34$. Now using this area ratio, we find the **subsonic solution** $M_2 = 0.5$, then using the normal shock relation, we find the overspeed Mach number $M_{overspeed} = 2.63$.

2.2 Normal Shock Diffuser

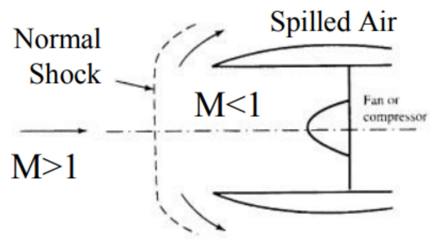

Figure 5: Normal Shock Inlet

This structure is simple, but it also has the **highest pressure loss due to strong shock**.

2.3 Oblique Shock Diffuser

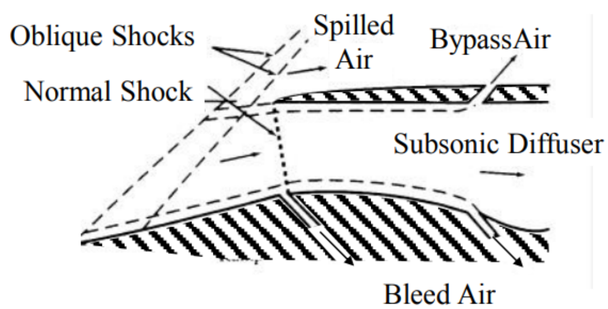

Figure 6: Oblique Shock Inlet

This structure has oblique shock(s) before the normal shock (usually inside inlet). This will lower the pressure loss and work for larger range of M.

3 Case Study: Normal vs Oblique Diffusers

3.1 Problem Setup

Assume 3 shock diffusers for $M = 2$ flight:

1. Normal shock diffuser with shock at inlet
2. Single oblique shock diffuser
3. Double oblique shock diffuser

Also assume air is TPG/CPG ($\gamma = 1.4$), steady, adiabatic, inviscid except for shock. We want to find the **pressure loss for each case.**

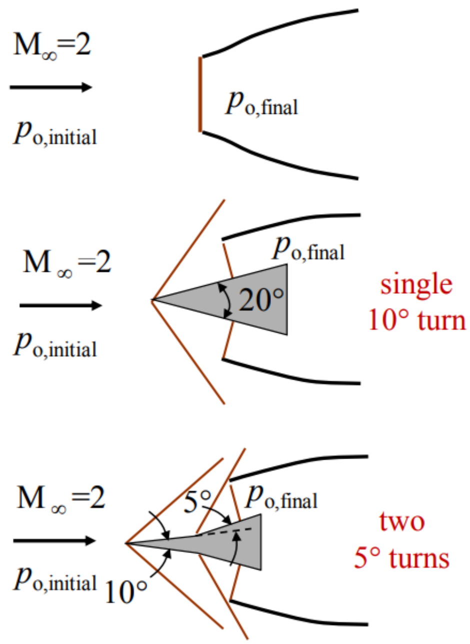

Figure 7: Problem Setup

3.2 Normal Shock

Easy normal shock relation:

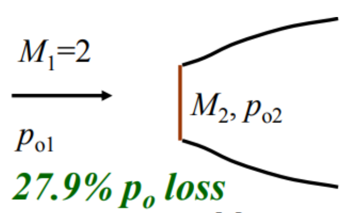

Figure 8: Normal Shock Case

$$M_1 = 2 \rightarrow M_2 = 0.577, \frac{p_{o2}}{p_{o1}} = 0.721 \tag{3}$$

So there is 27.9% p_o **loss.**

3.3 Single Oblique Shock (+Normal)

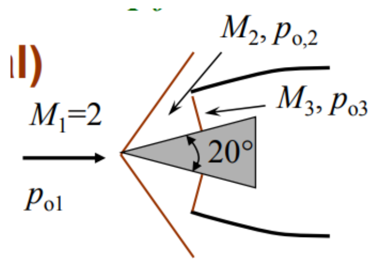

Figure 9: Single Oblique Shock Case

Start from oblique shock:

$$M_1 = 2, \delta = 10^o \rightarrow \theta = 39.3^o \tag{4}$$

Then we have the normal component:

$$M_{1n} = M_1 \sin\theta = 1.267 \tag{5}$$

Using normal shock relations

$$M_{2n} = 0.803,\ \ M_2 = \frac{M_{2n}}{\sin(\theta - \delta)} = 1.64 \tag{6}$$

$$\boxed{\frac{p_{o2}}{p_{o1}} = 0.985} \tag{7}$$

Then analyze the normal shock:

$$M_2 = 1.64 \rightarrow M_3 = 0.657 \tag{8}$$

$$\boxed{\frac{p_{o3}}{p_{o2}} = 0.88} \tag{9}$$

Finally we have the pressure ratio:

$$\boxed{\frac{p_{o3}}{p_{o1}} = \frac{p_{o3}}{p_{o2}}\frac{p_{o2}}{p_{o1}} = 0.867} \tag{10}$$

So there is 13.3% p_o loss.

3.4 Two Oblique Shocks (+Normal)

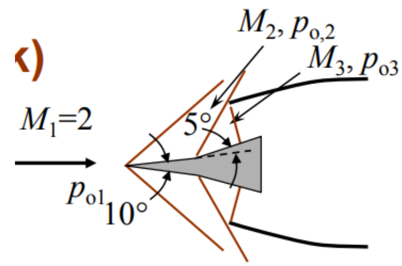

Figure 10: Two Oblique Shocks Case

Start from **first oblique**:

$$M_1 = 2, \delta_1 = 5^o \rightarrow \theta_1 = 34.3^o \tag{11}$$

Then we have the normal component:

$$M_{1n} = M_1 \sin\theta_1 = 1.127 \tag{12}$$

Using normal shock relations

$$M_{2n} = 0.891,\ \ M_2 = \frac{M_{2n}}{\sin\left(\theta_1 - \delta_1\right)} = 1.82 \tag{13}$$

$$\boxed{\frac{p_{o2}}{p_{o1}} = 0.998} \tag{14}$$

Then for the **second oblique shock:**

$$M_2 = 1.82, \delta_2 = 5^o \rightarrow \theta_2 = 37.9^o \tag{15}$$

Then we have the normal component:

$$M_{2n} = M_2 \sin\theta_2 = 1.12 \tag{16}$$

Using normal shock relations

$$M_{3n} = 0.897,\ \ M_3 = \frac{M_{3n}}{\sin\left(\theta_2 - \delta_2\right)} = 1.65 \tag{17}$$

$$\boxed{\frac{p_{o3}}{p_{o2}} = 0.998} \tag{18}$$

For the **normal shock:**

$$M_3 = 1.65 \rightarrow M_4 = 0.654 \tag{19}$$

$$\boxed{\frac{p_{o4}}{p_{o3}} = 0.8765} \tag{20}$$

Finally we have the pressure ratio:

$$\boxed{\frac{p_{o4}}{p_{o1}} = \frac{p_{o4}}{p_{o3}}\frac{p_{o3}}{p_{o2}}\frac{p_{o2}}{p_{o1}} = 0.873} \tag{21}$$

So there is 12.7% p_o **loss.**

4 Double Oblique Inlet

4.1 Advantages

For the same **final turn angle**, two oblique shocks are better than one in reducing pressure ratio. This effect will be improved with two larger angle turns. For two 10^o turns, only 4.3% pressure loss, so **larger overall deflection can give better** p_o**.**

4.2 Disadvantages

Since **static pressure increases across oblique shocks**, the flow will have **adverse pressure gradient**. With more or bigger oblique shocks, the greater chance **the boundary layer will separate**, which will cause major change in flowfield and large pressure losses.

Also, larger external flow turning requires **larger inlet**, which will also require **larger internal flow turning** to get flow aligned with **engine axis.**