Inlet External Drag[1][2]

1 Overview

A practical intake design involves many compromises, one of which is between **pressure recovery** and **inlet drag**. Here are some differences between them:

1. **Pressure Recovery:** determining factor of engine thrust, which is related to the resultant force **in the direction of flight** produced by the **internal flow**.

2. **Inlet Drag:** related to the resultant force **opposing the direction of flight**, produced by the **external flow.**

2 Thrust

The reckoning (a calculation or number you estimate) of drag in the **external flow** is consistent with the thrust in the **internal flow**.

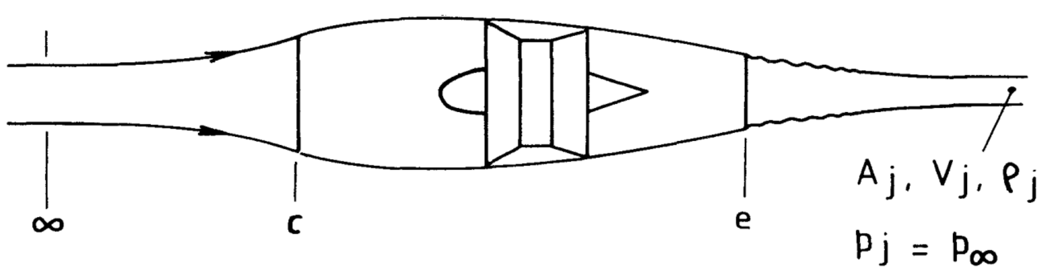

Figure 1: Thrust Definition

Consider the aerodynamic duct with engine enclosed, in an airstream extending from **upstream infinity** to **downstream infinity**, where the ambient pressure is restored to p_∞. Suffix j relates to condition with the **propulsive jet**. Therefore, we have the **overall thrust** (X_0) expression:

$$X_0 = \rho_j U_j^2 A_j - \rho_\infty U_\infty^2 A_\infty \tag{1}$$

However, this definition is not practical, because downstream of the exit the jet **mixes with the external flow in an imprecise way** so that the postulated conditions at downstream infinity are not in fact definable.

Therefore, we need to define thrust using **streamwise component of all internal pressures and surfaces within the duct**. The momentum flux now is between **entry and exit**, which yields the expression for **intrinsic thrust** (X_I):

$$X_I = [(p_e - p_\infty) + \rho_e U_e^2]A_e - [(p_c - p_\infty) + \rho_c U_c^2]A_c \tag{2}$$

However, this definition is still not that practical! The exit terms determined by the engine nozzle and related to test bed conditions. The entry terms will vary from one type of aircraft to another. Therefore, we use the momentum flux between **upstream infinity** and **exit station** to express the **net standard thrust** (X_N):

$$X_N = [(p_e - p_\infty) + \rho_e U_e^2]A_e - \rho_\infty U_\infty^2 A_\infty \tag{3}$$

We also define **gross thrust** as:

$$[(p_e - p_\infty) + \rho_e U_e^2]A_e \tag{4}$$

And the **momentum drag** as:

$$-\rho_\infty U_\infty^2 A_\infty \tag{5}$$

3 Drag

3.1 Pre-Entry (Additive) Drag

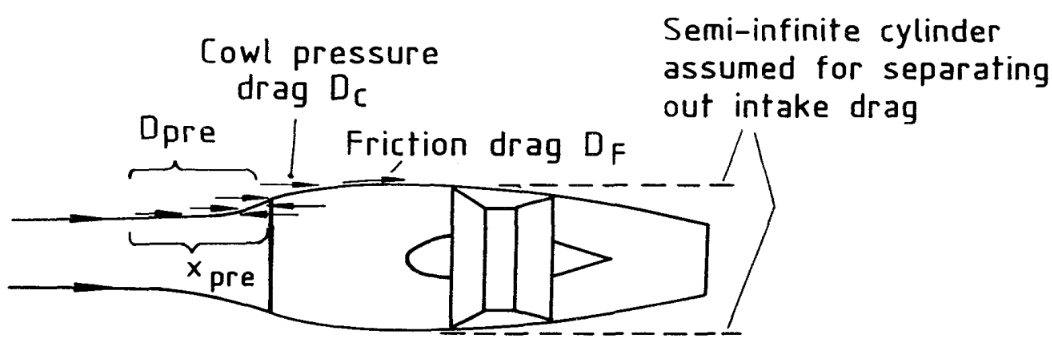

Fig. 9.2. Forces that comprise external drag.

Figure 2: Drag Definition

Drag terms on the cowl itself include **friction drag** (D_f), **pressure drag** (D_p**, in the picture is shown as** D_c). The difference between X_I and X_N is defined as the **pre-entry thrust force**. Here, we need to cancel this term by including an **an equal and opposite force in the drag definition**. Therefore, we introduce **pre-entry drag force** (D_{pre}):

$$D_{pre} = [(p_c - p_\infty) + \rho_c U_c^2]A_c - \rho_\infty U_\infty^2 A_\infty \tag{6}$$

Notice that this term is positive in the drag, as the flow ratio $A_\infty/A_c < 1$. This term is also called **additive drag.** The coefficient form is expressed as:

$$C_{D_{pre}} = \frac{D_{pre}}{q_\infty A_c} \tag{7}$$

And its dependence with Mach number is shown below:

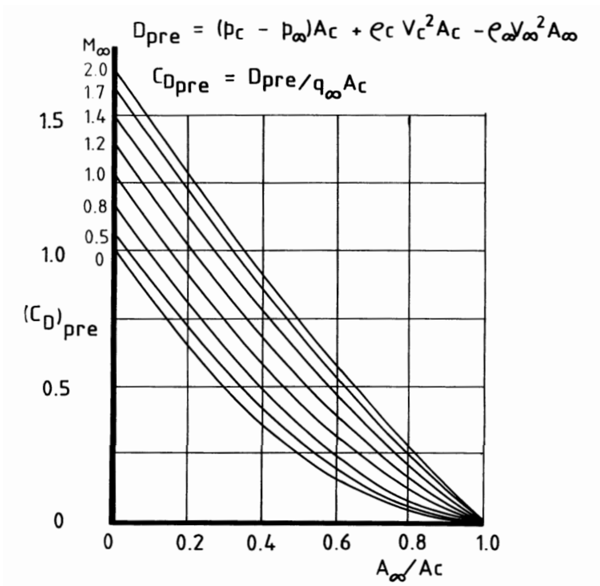

Figure 3: Pre-entry Coefficient Mach Number Dependence

3.2 Spillage Drag

Generally, we define the **inlet drag or cowl drag (D)** as:

$$D = D_f + D_p + D_{pre}(+D_{bleed}) \tag{8}$$

Where D_{bleed} is the boundary layer bleed drag or diverter drag. We can divide the cowl drag into its value at **full flow** ($A_\infty/A_c = 1$) and the change from that condition:

$$D = (D_f + D_p)_0 + \Delta D_0 + D_{pre} \tag{9}$$

Since additive drag is zero at **full flow**, the last two terms together express the change in drag caused by **variation from full flow to any other value**. This net effect is known as **spillage drag:**

$$D_{spill} = D_{pre} + \Delta D_0 \tag{10}$$

Another definition from NASA is that: spillage drag occurs when **inlet spills air around the outside, instead of conducting the air to the compressor face.** Some remarks:

1. The amount of air that goes through the inlet is set by the engine and changes with altitude and throttle setting.

2. The inlet is usually sized to pass the **maximum airflow** that the engine can ever demand and, for all other conditions, the inlet spills the difference **between the actual engine airflow and the maximum air demanded**.

3. As the air spills over the **external cowl lip**, the air accelerates and the **pressure decreases**. This produces a lip suction effect that partially **cancels out the drag due to spilling**. That's why when the flow ratio $A_\infty/A_c < 1$, ΔD_0 tends to be negative. We usually use K to be the correction factor of the suction effect.

Recall the NASA simplified inlet geometry:

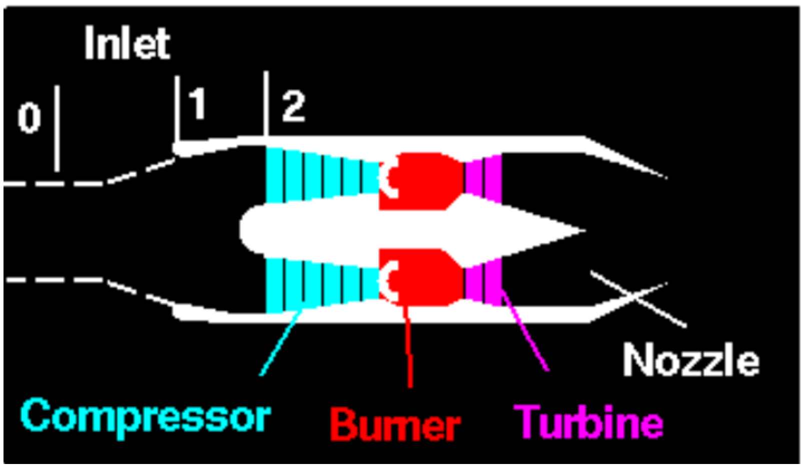

Figure 4: NASA Definition

A simplified version of spillage drag:

$$D_{spill} = K(m_1[U_1 - U_0] + A_1[p_1 - p_0]) \tag{11}$$

4 Compressor Stall

What is the compressor stall and how does it happen?

1. As the air is brought from free stream to the compressor face, the flow may be **distorted** by the inlet.

2. At the **compressor face**, one portion of the flow may have a higher velocity or higher pressure than another portion.

3. Because of this, the flow may be swirling, or some section of the boundary layer may be thicker than another section because of the inlet shape.

4. As the rotor blades encounter **distorted inlet flow**, the flow conditions around the blade change very quickly.

5. The changing flow conditions can cause **flow separation in the compressor, a compressor stall**, and can cause structural problems for the compressor blades.

6. A good inlet must produce **high pressure recovery, low spillage drag, and low distortion**.

References

[1] J. Shedon and E. L. Goldsmith. *Intake aerodynamics*. Blackwell Science, 1999.

[2] URL https://www.grc.nasa.gov/www/k-12/airplane/inleth.html.