Jet engine inlets
and ducts

by
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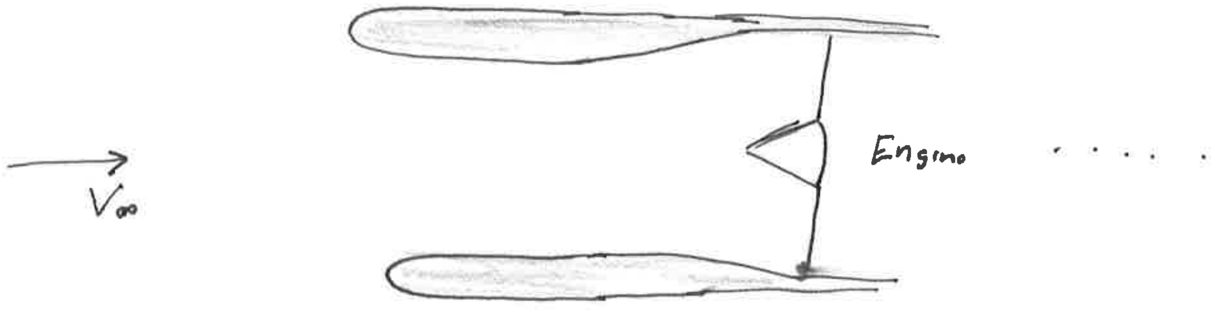
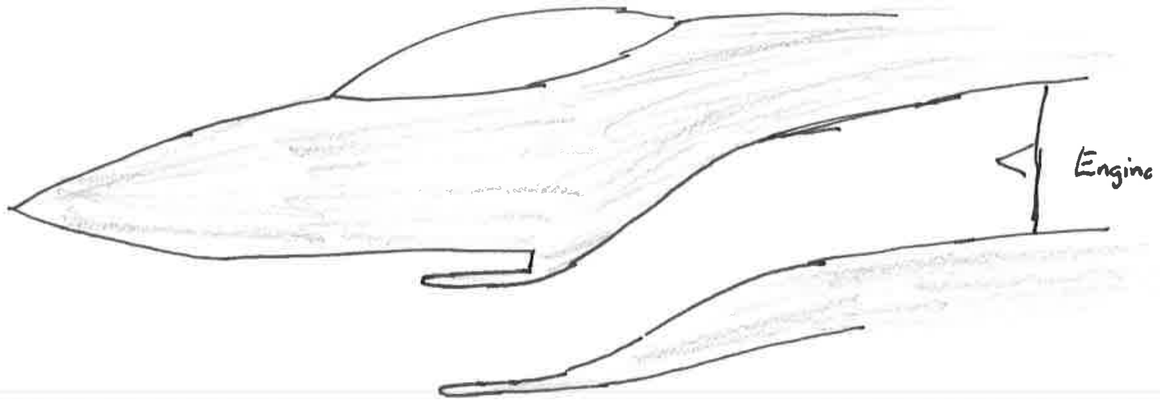
The objective of a duct is to take the exterior flow, slow the fluid down, and introduce the fluid to the engine fan face.

This can be a complex task.

The duct/inlet must operate over a wide range of

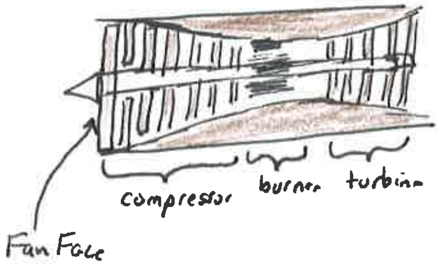
- Mach # / Flight V_∞
- α and β
- Power settings

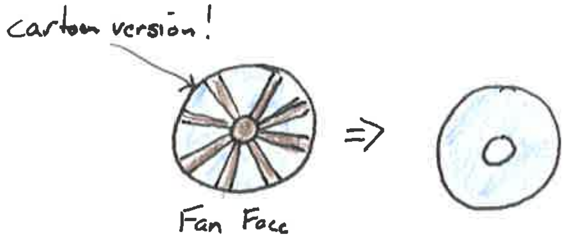




Jet Engine Fan Face

To operate efficiently, the engine needs a uniform flow delivered to the fan face

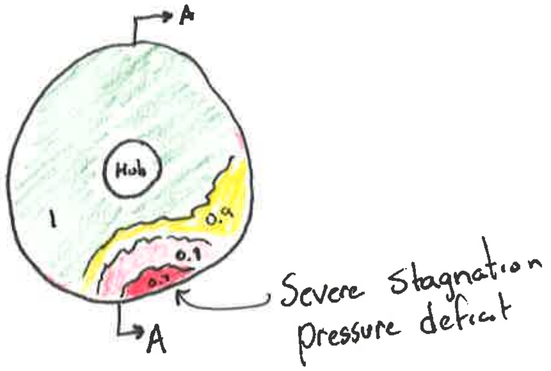


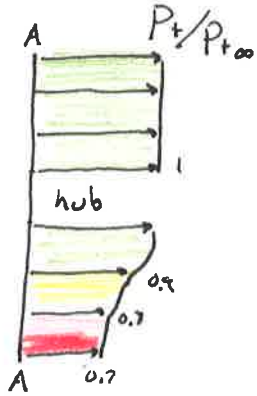


The typical uniform flow criteria are

- Stagnation Pressure Ratio ← $\dfrac{\text{Total Pressure at the fan face}}{\text{Total pressure in Flow}}$
- Flow angularity
- .... Flow unsteadyness
- ....

Fan Face with iso contours of $P_t/P_{t\infty}$





A loss of P_t corresponds to a non-isentropic process:

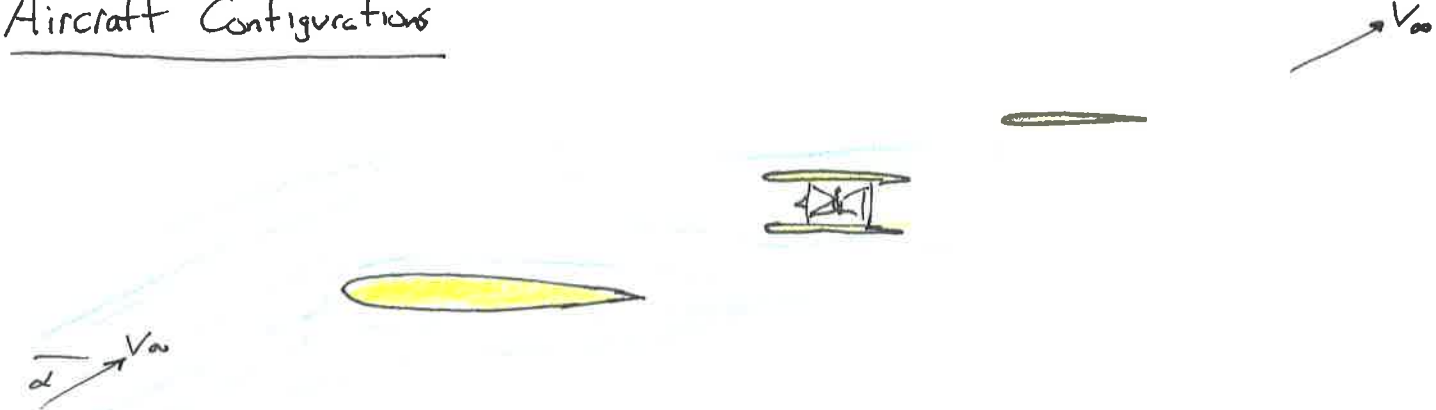
- Boundary layers
- Separation
- Shocks

} basically any irreversible process

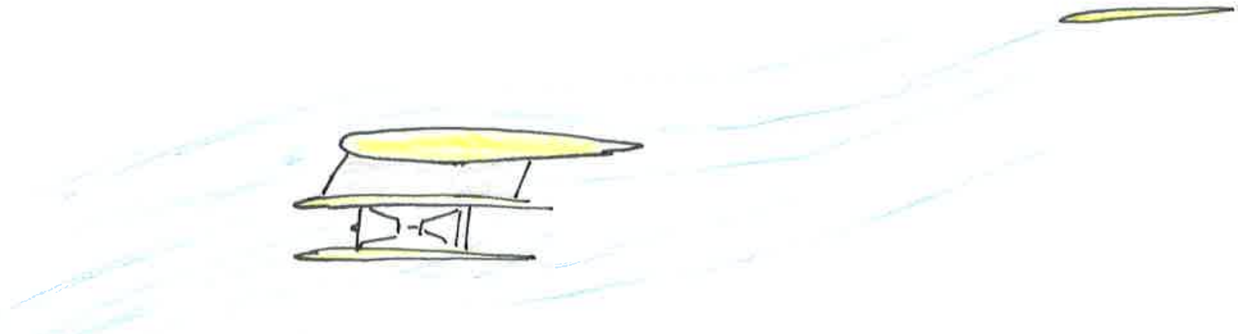
Worse, the fan blades will move through varying velocities ⇒ vary α ⇒ vary L

High Cycle Fatigue and Vibration!

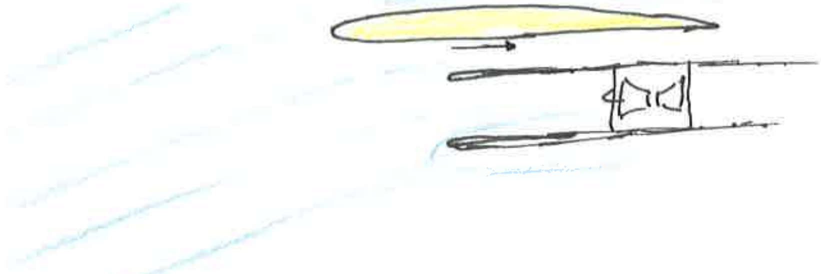
Aircraft Configurations



Business jet



Transport Aircraft



Fighter jets

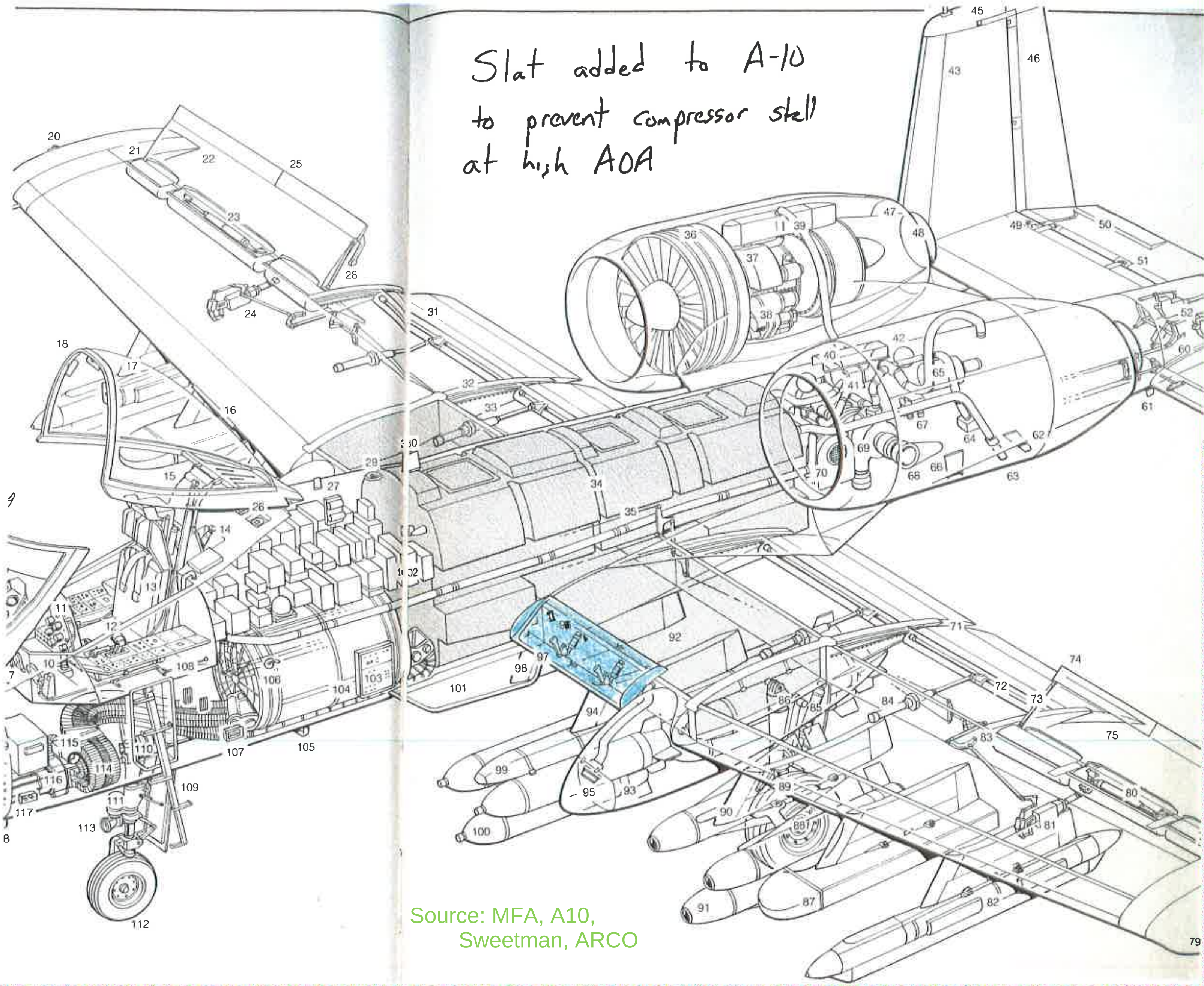
Dirty Air

Separated, unsteady, large $P_t/P_{t\infty}$ ratios

What occurs when the engine injests "dirty air"?

Usually compressor stall

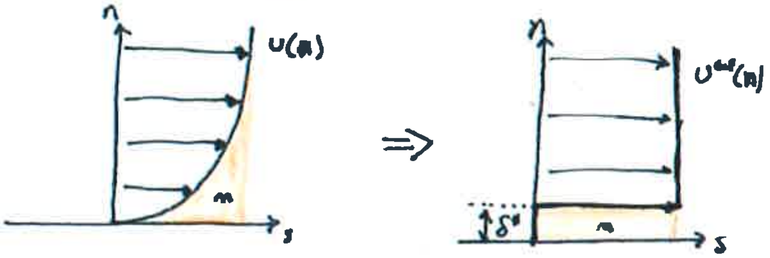
Mitigate by keeping flow attached on wings.



Slat added to A-10 to prevent compressor stall at high AOA

Source: MFA, A10, Sweetman, ARCO

Mass displacement thickness



$$\delta^* \equiv \int_0^{n_e} \left(1 - \frac{\rho u}{\rho_e u_e}\right) dn \qquad \text{and} \qquad \text{mass defect} \equiv m \equiv \rho_e u_e \delta^*$$

$$= \int_0^{n_e} (1 - U)\, dn \quad \text{(incompressible)} \qquad \omega \quad U = \frac{u}{u_e}$$

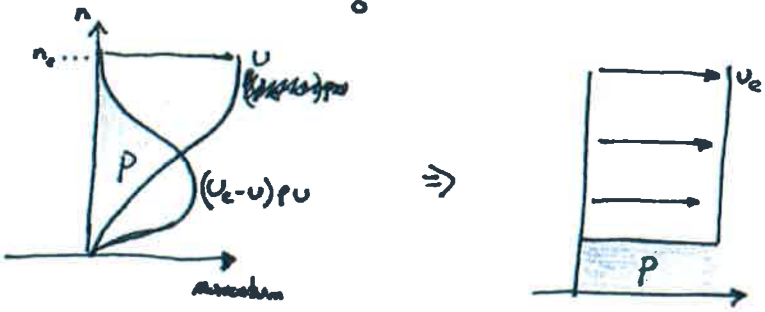
Momentum Thickness

$$\theta \equiv \int_0^{n_e} \left(1 - \frac{u}{u_e}\right) \frac{\rho u}{\rho_e u_e}\, dn = \underbrace{\int_0^{n_e} (U - U^2)\, dn}_{\text{incomp' only}}$$

and the momentum defect

$$P = \int_0^{n_e} (u_e - u)\, \rho u\, dn = \rho_e u_e^2 \theta$$

where have we seen P before?
Drag' = P



Energy Thickness

$$\theta^* \equiv \int_0^{n_e} \left(1 - \frac{u^2}{u_e^2}\right) \frac{\rho u}{\rho_e u_e}\, dn$$

and the energy defect

$$K = \int_0^{n_e} \frac{1}{2} (u_e^2 - u^2)\, \rho u\, dn = \frac{1}{2} \rho_e u_e^3 \theta^*$$

Integral Boundary Layer Relations

Take mass and momentum equations and combine to $(u_e - u)\cdot(\text{Mass equ}) - (\text{mom equ}) =$

$$\frac{d}{ds}\left(\rho_e u_e^2 \theta\right) = \tau_w - \rho_e u_e \delta^* \frac{du_e}{ds}$$

or

$$\boxed{\frac{dp}{ds} = \tau_w + \delta^* \frac{dp}{ds}}$$

Momentum defect (i.e. drag) results from surface shear stress and an increase of pressure in the presence of a boundary layer.

The dimensionless form is

$$\frac{d\theta}{ds} = \underbrace{\frac{C_f}{2}}_{\text{skin friction coeff'}} - \left(\underbrace{H}_{\text{shape parameter}} + 2 - \underbrace{M_e^2}_{\text{edge Mach \#}}\right)\frac{\theta}{u_e}\underbrace{\frac{du_e}{ds}}_{\text{pressure gradient equivalent}}$$

<u>ODE</u>

$$H = \frac{\delta^*}{\theta}$$

$$\boxed{\frac{d\theta}{ds} \approx \frac{C_f}{2} + \left(H + 2 - M_e^2\right)\frac{\theta}{\rho_e u_e^2}\frac{dp}{ds}}$$

$H_{\text{blasius BL}} \approx 2.59$

$H_{\text{turb}} \approx 1.4$

Above $M_e \approx 1.8_{\text{turb}}$ to 2.1_{blasius}, the sign of $(H + 2 - M_e^2)$ switches.

Below $M_e \approx 1.8$, $\frac{dp}{ds} > 0$ increases θ. Above, $\frac{dp}{ds} < 0$ increases θ

See FVA Chapter 4.5 for additional information

↑

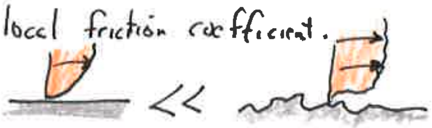
Flight Vehicle Aerodynamics, Drela

$$\boxed{\frac{d\theta}{ds} = \frac{C_f}{2} + \left(H + 2 - M_e^2\right)\frac{\theta}{\rho_e U_e^2}\frac{dp}{ds}}$$

Ducts are naturally creating an adverse pressure gradients, which makes the BL thicker.

θ is a measure of the boundary layer thickness and impact on drag. "Momentum thickness"

C_f : local friction coefficient.



$H \equiv$ shape parameter ≈ 1.4 turb

$\frac{dp}{ds}$: pressure gradient along streamline at surface

Q: Given zero pressure gradient, how does θ evolve?

θ is a measure of the momentum thickness (i.e. drag up to that point)

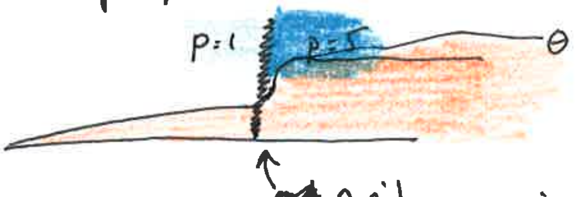
$$\frac{d\theta}{ds} = \frac{C_f}{2} + \cdots \overset{\frac{dp}{ds}=0}{\cancel{\theta}} \cdots$$

Drag depends of surface friction only when $dp/ds = 0$

Q: Given a strong adverse pressure gradient $\left(\frac{dp}{ds} \gg 0\right)$, how does θ evolve?

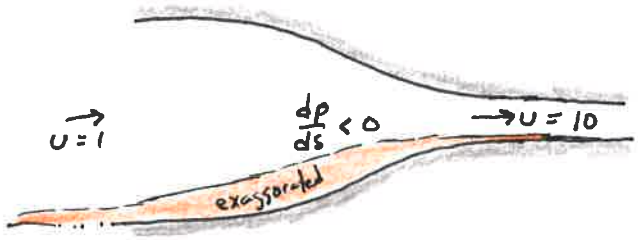
$$\frac{d\theta}{ds} = \frac{C_f}{2} + \left(H + 2 - M_e^2\right)\frac{\theta}{\rho_e U_e}\overset{\text{very large}}{\cancel{\frac{dp}{ds}}}$$

θ increases rapidly. We see this aft of shocks.



rapid increase in θ near $\frac{dp}{ds} \gg 0$

Q: Give a wind tunnel contraction, how does θ evolve?



$$\frac{d\theta}{ds} = \frac{C_f}{2} + \left(H + 2 - M_e^2\right)\frac{\theta}{\rho_e U_e}\overset{\text{negative}}{\cancel{\frac{dp}{ds}}}$$

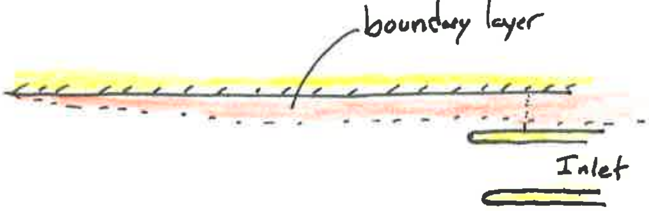
if $\frac{dp}{ds} < -\frac{C_f}{2}\left(\frac{1}{H+2}\right)\left(\frac{\rho_e U_e}{\theta}\right)$ then the BL thins!

Bernoulli's equ.

$$\frac{1}{2}\rho V_1^2 + P_1 = \frac{1}{2}\rho V_2^2 + P_2 \Rightarrow P_2 - P_1 = \frac{1}{2}\rho\left(\overset{1^2}{\cancel{V_1^2}} - \overset{10^2}{\cancel{V_2^2}}\right) \Rightarrow P_2 << P_1 \quad \frac{dp}{ds} < 0$$

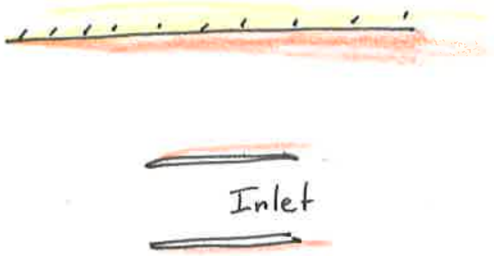
Duct Mitigation Strategies

- Inlet outside of BL. / splitter plate



F-16 and <u>many</u> others

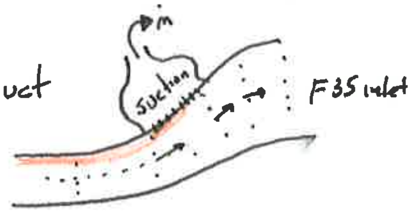
- Pod engine (extreme form of above)



- Nose Inlet / wing inlet

F-86 F-100
M.G 15, 17, 21 . . . .

Serpentine duct

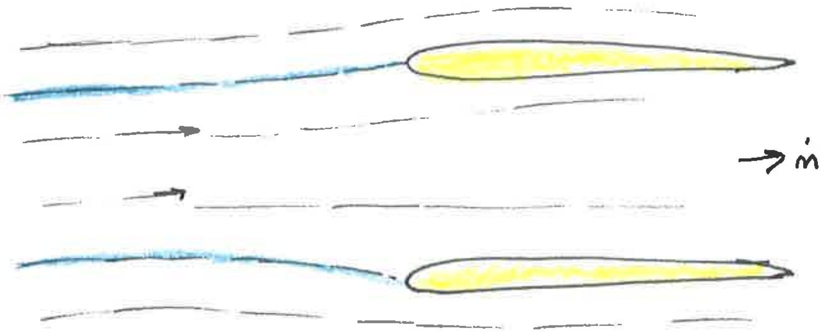


- Diverterless Inlet

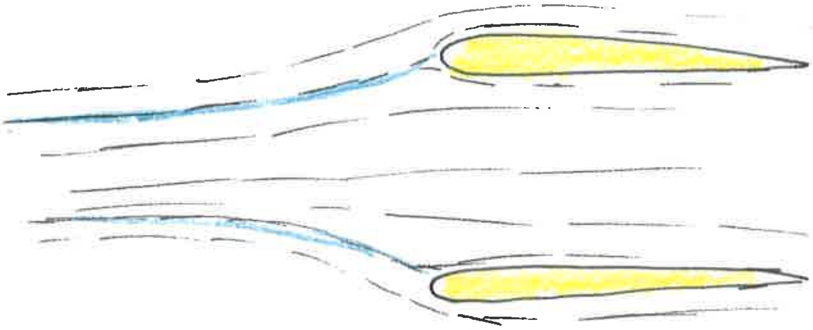
Aerodynamic bump to "divert" thick BL away from inlet
Compatible with stealth

F-35

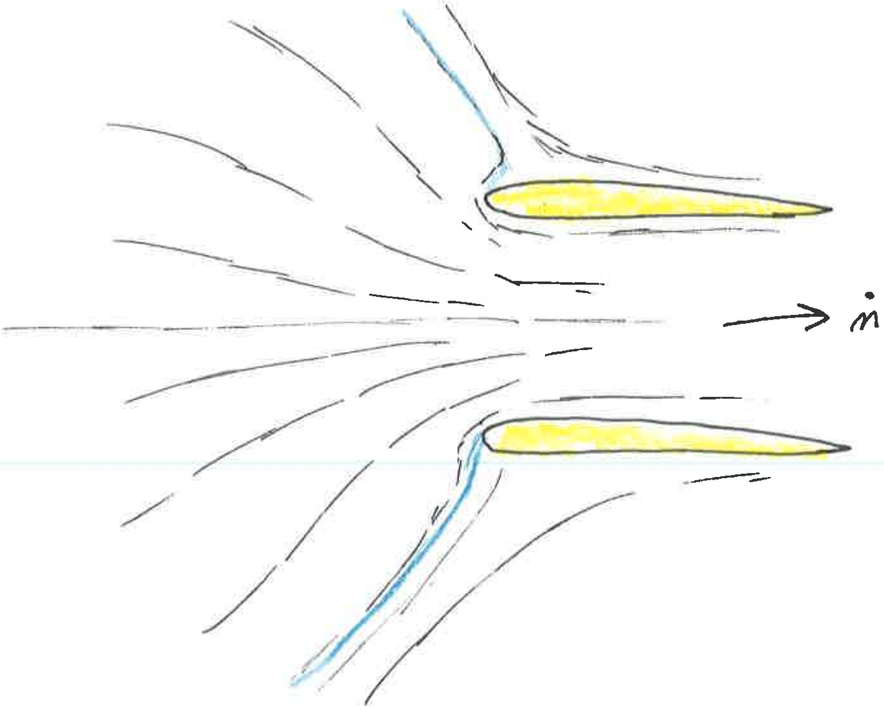
Flight Conditions



On design, medium speed

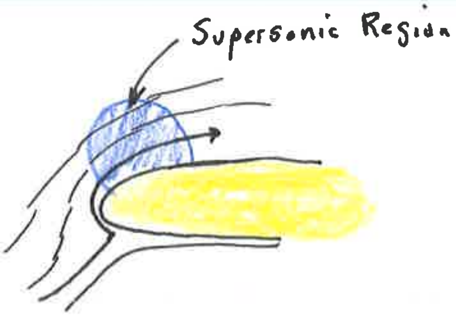


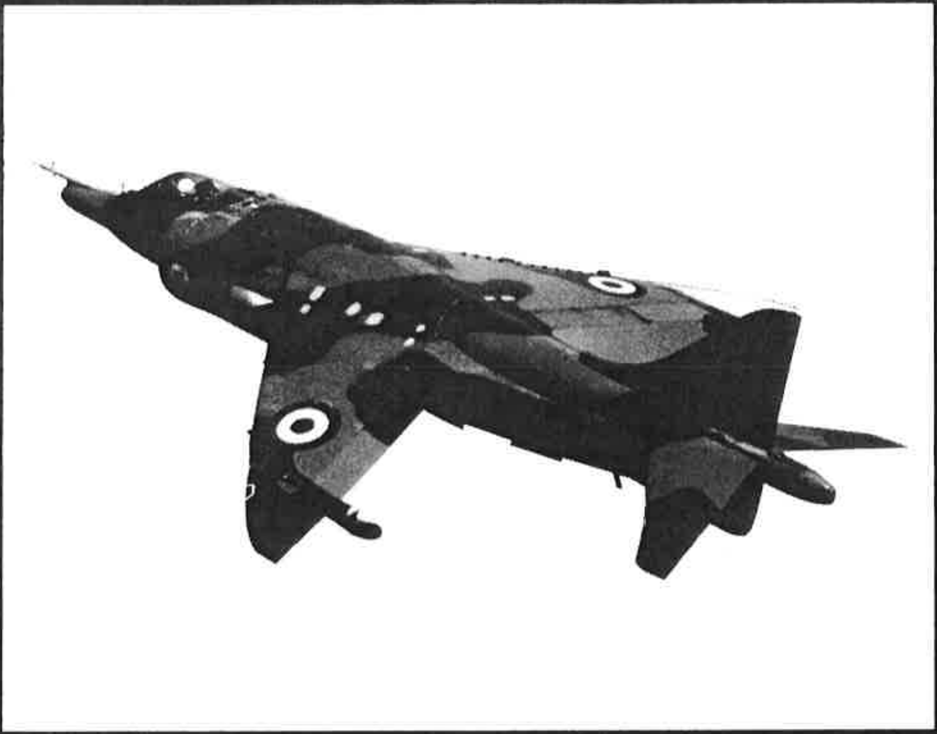
High Speed



High $\dot{m}$, Low speed

Takeoff





AIAA
PROFESSIONAL STUDY SERIES

THE BRITISH AEROSPACE HARRIER CASE STUDY IN AIRCRAFT DESIGN

BY
JOHN W. FOZARD
Executive Director and
Chief Designer, Harrier
British Aerospace, Aircraft Group

3.2 Aerodynamic Design – Air Intake

INTRODUCTION

With a vertical take-off aircraft like the Harrier, the only ground attack/reconnaissance jet V/STOL weapons system in operational service today, the air intakes have a vital influence on design and performance. At lift-off and landing they need to absorb an exceptionally large flow of air with minimum loss. This demands a relatively large intake, which in turn increases the difficulty of keeping down drag during high speed flight. These design problems had to be met whilst providing also the ability to accept violent manoeuvring throughout all phases of the operational envelope.

Basically, air intakes are simply ducts to conduct air to the engine in such a way that the compressor can function without causing much loss of thrust, or stalling with a bang ('surging'), or loss of pieces off compressor blades through vibration. However, on the Harrier the outsides of the intakes also matter because the external drag could, with bad design, be enormous during high speed flight at low altitudes. Further, it is important to keep the weight low, under local pressure loadings that range from roughly 6 pounds per square inch suction to 10 pounds per square inch pressure.

VERTICAL TAKE-OFF CONDITIONS

The most critical task for the Harrier intakes occurs with the engine at full throttle during vertical take-off and landing – consuming over 10 tons of air per minute (equivalent to the volume of forty average houses). For the Rolls-Royce Bristol Pegasus vectored-thrust engine, one per cent of loss of total pressure (due to friction and turbulence in the intake) causes perhaps two per cent loss of thrust. Thus, if the nominal fuel load were (say) one-sixth of the take-off weight, it would follow that one per cent loss of total pressure in the intake would lose 12 per cent of the range, and eight per cent loss of the total pressure would eliminate vertical take-off – unless ordnance load was exchanged for fuel. Thus the aerodynamic development of the intakes for VTO conditions was a thorough and detailed process, combining theory and experiment at every stage.

How can one ensure the lowest possible losses in an air intake? First it is necessary to understand how losses originate. Fig.3.2.1 represents a horizontal section through the air intakes of a Harrier-type aircraft. From the sketched streamlines it can be seen that at zero flight speed the entering air reaches high speeds past the lips of the intakes, depending on the average speed through the throat and the smallness of the bellmouth area.

If no turbulence develops, the kinetic energy of any particle of entering flow could be converted without loss back into pressure energy by slowing it down again, but turbulence arising from any disturbance (such as frictionl excrescences, vortex formation, or mixing between airstreams at different speeds) makes it impossible to recover the full original pressure of the airflow by slowing it down.

The pressure developed by airflow slowed down to rest without extra losses is known as the 'total pressure', and any additional turbulence reduces the total pressure. The ratio of the total pressure at the exit of the intake to that of the smooth external flow is known as the 'pressure recovery factor', here termed the 'efficiency' for short. For any given air intake, the loss of efficiency is roughly proportional to the maximum kinetic energy of the entering airflow.

Theory shows that the maximum airspeed into a round-lipped intake increases as the area of the bellmouth reduces, and more recent theory allied to tests shows that the efficiency at the throat of smooth round-lipped intakes can be represented as a formula as in Fig. 3.2.2. Extra losses can arise downstream of the throat.

High altitude climb conditions dictated that the throat airspeed at V.T.O. should not exceed perhaps 70 per cent of the local speed of sound (i.e. throat Mach number $M_t = 0.70$), but high speed low altitude flight requires the throat area to be kept as small as possible – so the throat Mach number is confined fairly close to the region of two-thirds ($M_t \simeq 0.67$). From Fig.3.2.2 can be seen that to secure efficiency much above 95 per cent at practical throat airspeeds it is essential to provide bellmouth area exceeding about half the throat area.

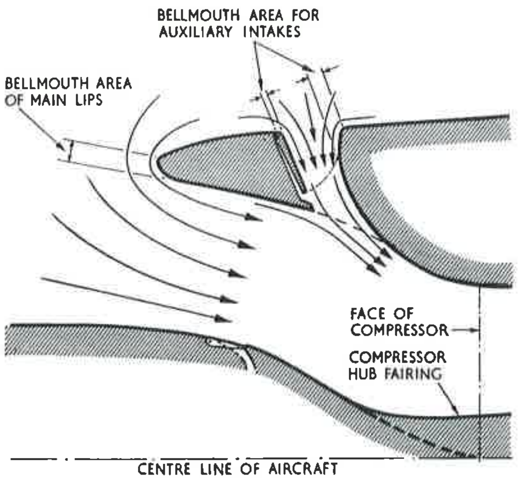


Fig.3.2.1 Intake flow pattern in V/STOL and definitions

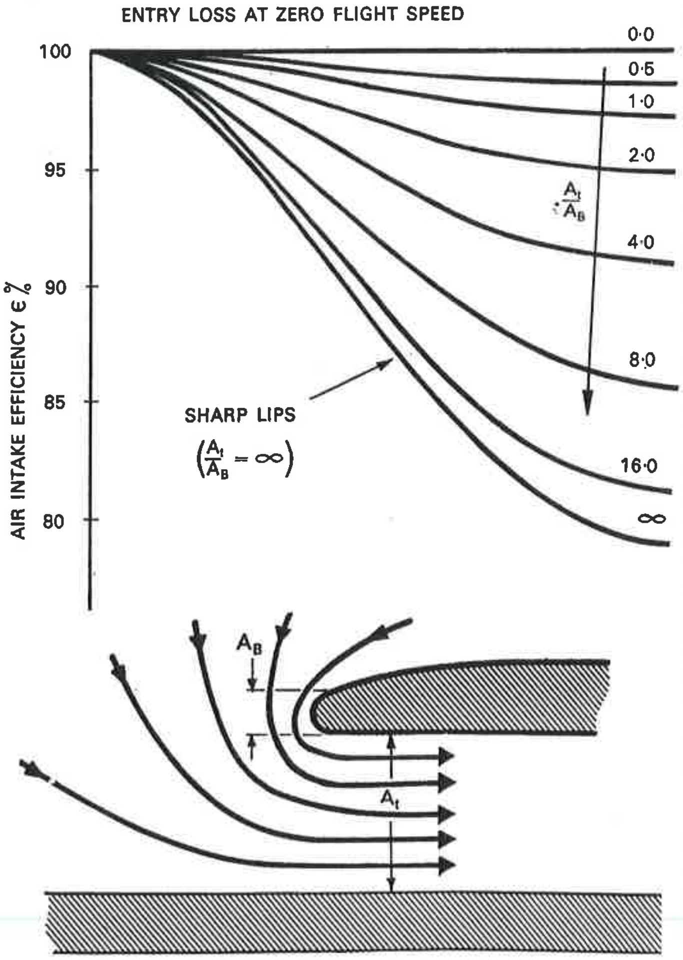


Fig.3.2.2 Theoretical efficiency of round-lipped inlets in hover

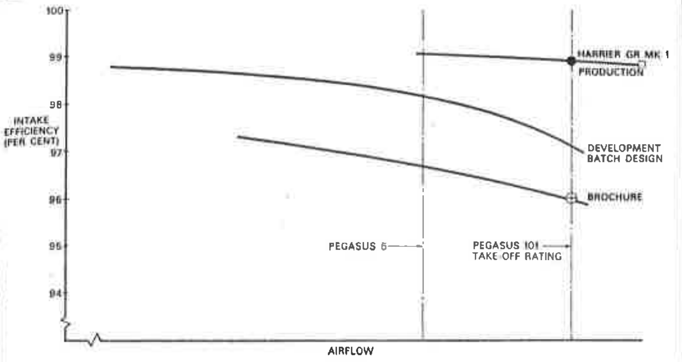


Fig.3.2.3 Harrier intake efficiency in hover

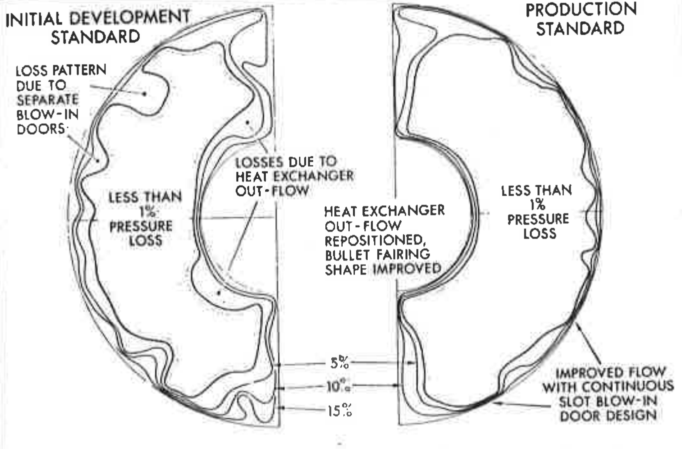


Fig.3.2.4 Flow distribution in hover showing reduced hub loss in the production configuration

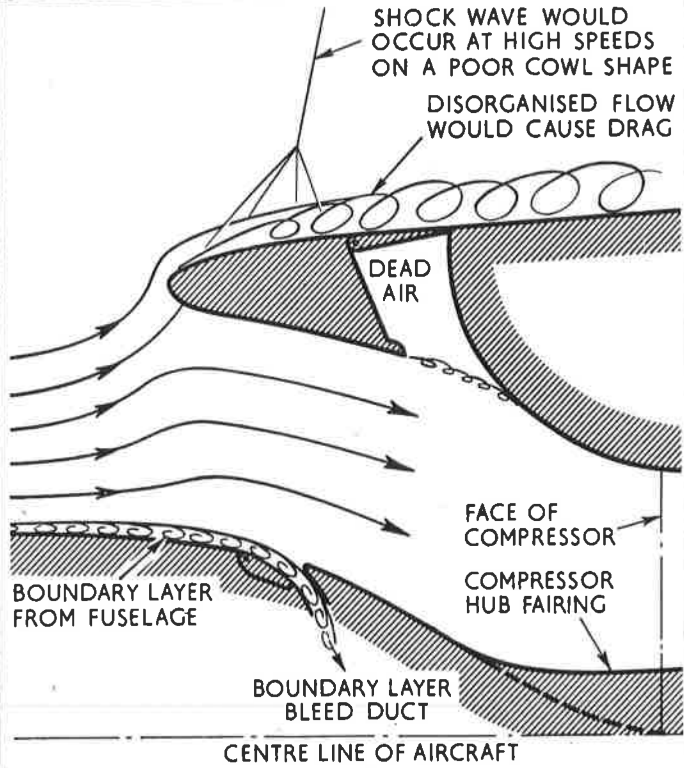


Fig.3.2.5 Potential sources of spillage drag on an intake in flight at high speed. Note how the boundary layer bleed slot opens under spilling conditions

Thick lips on an air intake can cause enormous drag during high speed flight, and it was necessary to devise a scheme whereby the bellmouth area provided for VTO does not prohibitively invoke such a condition. Variable geometry schemes immediately come to mind, for example hinged-cowl or translating-cowl mechanisms that retract for high speed flight. On the earlier P.1127 prototypes, an elastic rubber sheath was stretched around a conventional high speed intake cowl and inflated to a large radius bellmouth for VTOL, but maintenance promised to remain expensive and a cheaper solution was sought for the Harrier (which has to deal with much more airflow in any case).

The solution adopted was to provide auxiliary air intakes all around the cowl of the main intake, such that the auxiliary bellmouth area faces laterally, and thus does not add to the thickness of the main intake lips (see Fig.3.2.1). Since the original proposal was to guarantee an efficiency of not less than 96 per cent at full throttle, there was very little room for any mixing losses that would arise if airstreams of different speeds and directions had to merge. Accordingly, the auxiliary and main ducts were all designed for over 97 per cent efficiency – which meant providing well-shaped passages of the correct proportions everywhere.

Simple hinged doors were provided which suck in when the pressure inside the intake is less than that outside (as in flight at low speeds) and they close against stops to form a smooth outer shape when the internal pressure is high. It so happens that whenever these doors (with no actuators or springs) operate automatically under air pressures, the efficiency of the intake is generally improved.

AERODYNAMIC TESTING FOR VTOL CONDITIONS

The first phase of model testing investigated the suction performance of the original design of intakes for the Harrier, in relation to the effects of vertical jets blowing, headwinds, the presence of the ground and so on. This testing (using a quarter-scale half model) concluded that the intake efficiency was about one per cent above guarantee under the worst combination of jet interference and ground effect. However, this was very far from the end of the story, for tests of a full-scale intake with engine indicated thrust losses roughly double what had been expected!

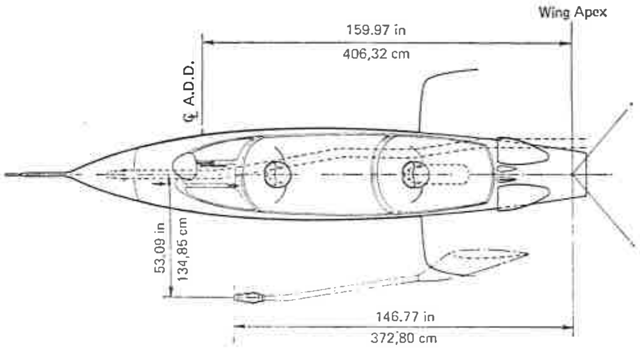
Research soon showed that the efficiency of the full-scale intake was practically the same as the model, but the Pegasus compressor appeared to suffer losses sensitively when presented with patches of low speed airflow near the hub. The original model was soon joined by a model initially intended as a later development, having the auxiliary inlets merging at the inner surface of the main duct into virtually a continuous slot. These two models were tested alternately, so that testing proceeded on one while modifications were in progress on the other. Every test recorded 120 total-pressure readings, and in this series well over 100 configurations were tested – involving variations of shape of the auxiliary inlet ducts, lips and compressor hub-fairing – and various arrangements of vortex generators, boundary layer fences and an air outlet from an internal system.

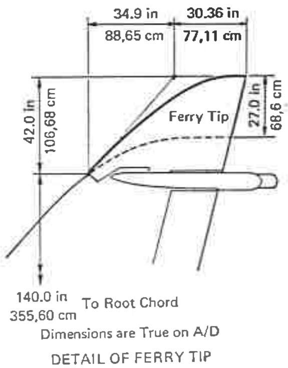
Losses near the hub were reduced by refining the hub fairing shape and redesigning the system outlet. Changes to the auxiliary inlets also were very significant – showing a useful gain of overall efficiency for the more radical design. This form of intake was chosen for the production Harrier, in view of its better range and its potential for accepting the next Pegasus engine uprating without redesign. Fig.3.2.3 shows the efficiency achieved by the production design compared with the original design ('Development Batch') and the brochure prognostication. Fig.3.2.4 illustrates the improvements of total-pressure distribution, obtained during this development programme.

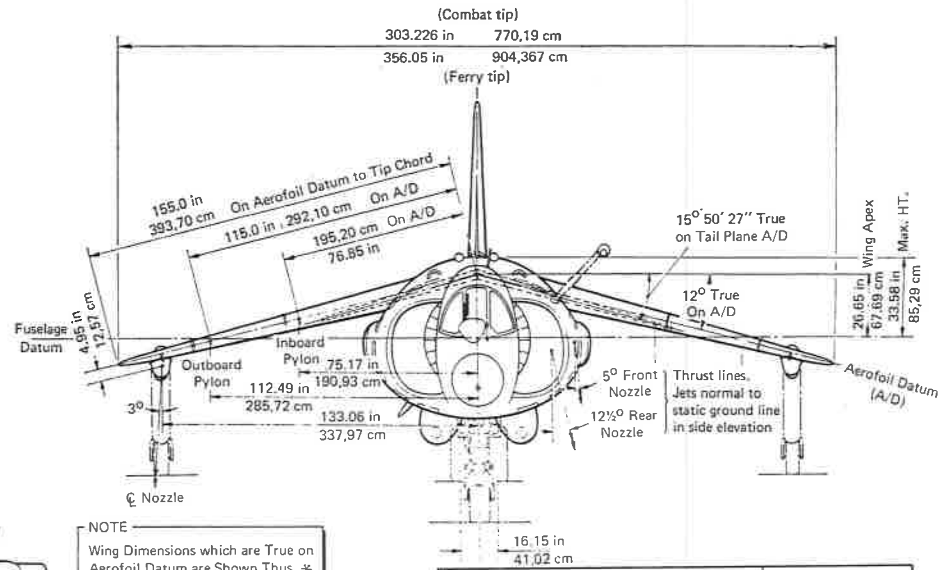
FORWARD FLIGHT OPERATION: SPILLAGE DRAG

The air intakes are relatively large for VTOL purposes. For conventional flight the airflow required by the engine is not abnormal, so it follows there is a modest amount of air going into a big intake; in other words, a relatively large 'spillage'. This always increases as the altitude of flight is lowered, so that the Harrier (which has to operate much of its service at low altitudes) has to cope with an abnormally large spillage for much of the time.

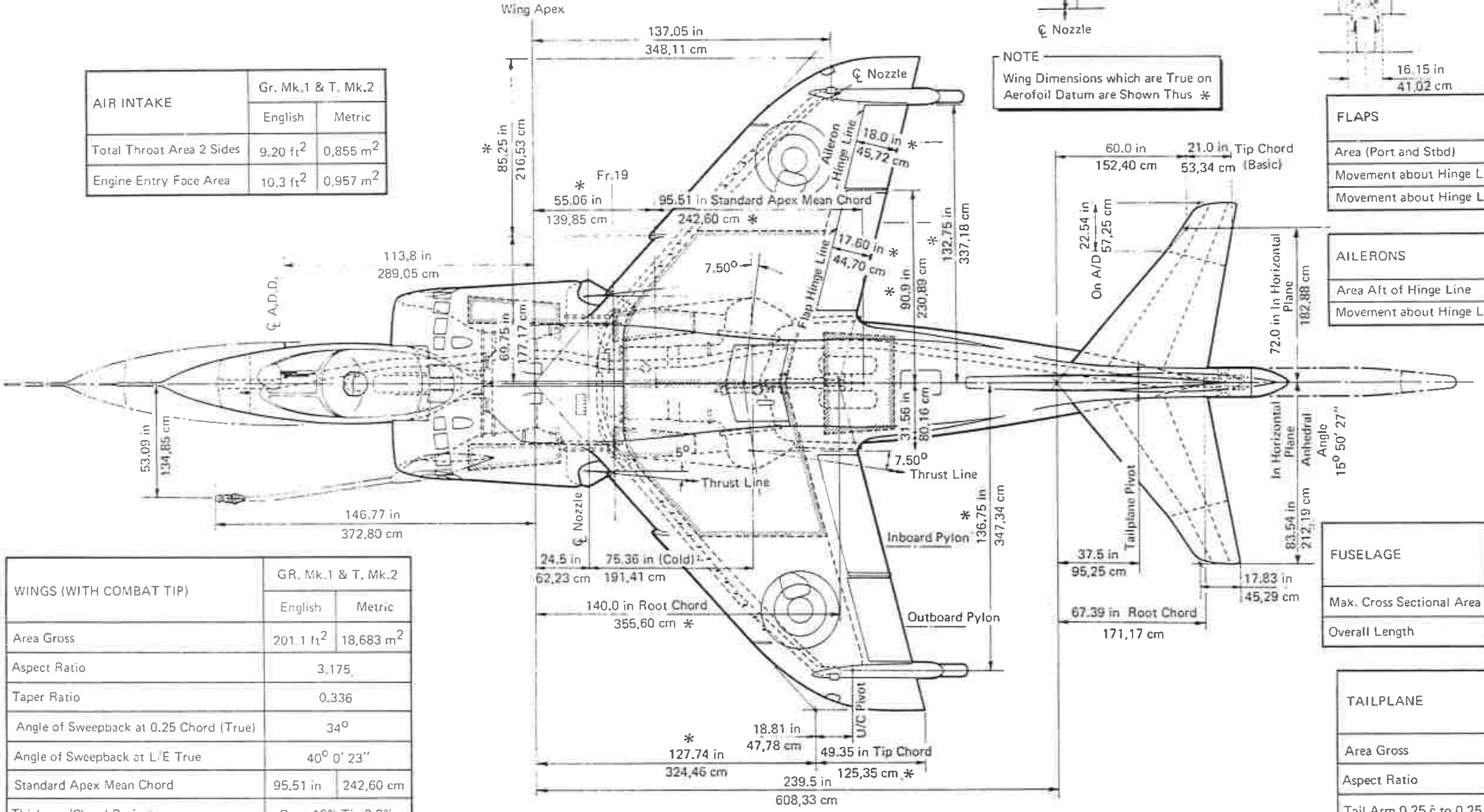
Why worry about airflow spillage? Fig.3.2.5 sketches the sort of streamline pattern that might occur if the spillage gets too large. The airflow diverted outwards past the lips of the air intake reaches high







NOTE
Wing Dimensions which are True on Aerofoil Datum are Shown Thus *



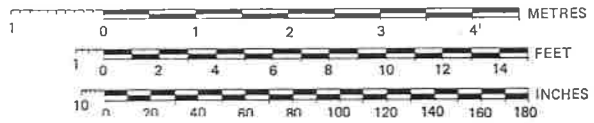
AIR INTAKE	Gr. Mk.1 & T. Mk.2	
	English	Metric
Total Throat Area 2 Sides	9.20 ft²	0,855 m²
Engine Entry Face Area	10.3 ft²	0,957 m²

FLAPS	Gr. Mk.1 & T. Mk.2	
	English	Metric
Area (Port and Stbd)	13.9 ft²	1,291 m²
Movement about Hinge Line (Take Off Setting)	50° Nom.	
Movement about Hinge Line (Manoeuvre Setting)	17° Nom.	

AILERONS	GR. Mk.1 & T. Mk.2	
	English	Metric
Area Aft of Hinge Line Port and Stbd	10.54 ft²	0,979 m²
Movement about Hinge Line	High Speed ± 9° 24′ Low Speed ± 12°	

WINGS (WITH COMBAT TIP)	GR. Mk.1 & T. Mk.2	
	English	Metric
Area Gross	201.1 ft²	18,683 m²
Aspect Ratio	3.175	
Taper Ratio	0.336	
Angle of Sweepback at 0.25 Chord (True)	34°	
Angle of Sweepback at L/E True	40° 0′ 23″	
Standard Apex Mean Chord	95.51 in	242,60 cm
Thickness/Chord Ratio	Root 10% Tip 3.3%	

WINGS (WITH FERRY TIP)	GR. Mk.1 & T. Mk.2	
	English	Metric
Area Gross	215.9 ft²	20,058 m²
Aspect Ratio	4.078	



FUSELAGE	Gr. Mk.1		T. Mk.2	
	English	Metric	English	Metric
Max. Cross Sectional Area	30.31 ft²	2,816 m²	32.80 ft²	3,047 m²
Overall Length	45.55 ft	1388,36 cm	55.90 ft	1703,85 cm

TAILPLANE	Gr. Mk.1 & T. Mk.2	
	English	Metric
Area Gross	47.54 ft²	4,417 m²
Aspect Ratio	4.079	
Tail Arm 0.25 c̄ to 0.25 c̄ Wing	16,615 ft	506,42 cm
Mean Chord	3.414 ft	104,06 cm
Tailplane Movement	+ 11° 15′ : − 10° 15′	
Angle of Sweepback at 0.25 Chord (True Inbd)	32° 53′ 25″	
Angle of Sweepback at L/E (True Inbd)	38° 43′ 7″	
Thickness/Chord Ratio	Root 7%, Tip 7%	

Engine Deck

Actual engines come in discrete sizes.

When designing an aircraft, you need to know the engine performance at many flight conditions

Engine manufacturers create $\underbrace{\text{engine models and tabulated data}}_{\text{Engine Deck.}}$

Closely held without an NDA on other agreement.

Date:

M, $\dot{m}$, Thrust, pressure ratios, Turbine exit temp, surge?, flow rate of fuel, etc.