Air Intake Design

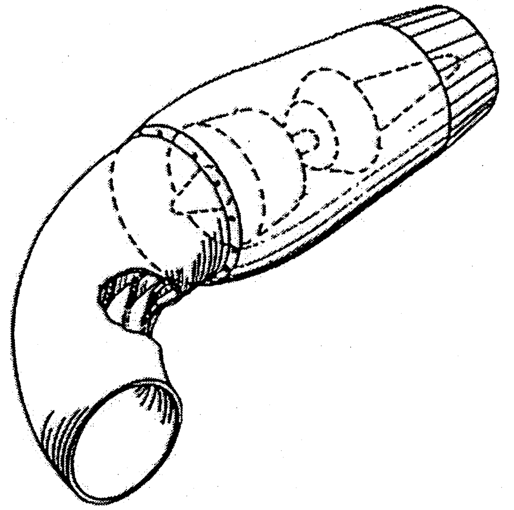

Figure 1: Curved air intake extender with engine.

Figure 1 shows a preferred embodiment of a generic reaction engine(s).The engine(s) are preferably turbojets, having a compression stage, a combustion stage, and a turbine stage to drive the compressor stage. Power is provided by the thrust of the expanded gas as it leaves the exhaust stage.

The air conduit bends from a longitudinal to a transverse posture from the air inlet disc to the reaction engine. Internal vanes are mounted within the conduit in order to facilitate a generally uniform flow stream around the curved portions of the conduit. The reaction engine may be releasably connected to the extremity for a support arm by the provision of a mounting saddle having thrust mounting blocks and a plurality of circumferential mounting collars.

Air Intake Design For Thrust Architecture

ABSTARACT: The problem of air intake design is to ensure that a gas turbine engine is properly supplied with enough amount air under all conditions of operation with an acceptable level of pressure loss. The ***THRUST ARCHITECTURE*** anticipated this loss in pressure and found a solution to this phenomenon by controlling the air input level and rate, by adjusting the air flowing into the air inlet (that is from an external supply source through sufficient air intake ducts) that would rotate commensurate with the rotation of each engine. These engine air supply inlet ducts would also preclude the engines from ingesting unwanted external physical debris that might cause engine failure or damage. The loss due to geometry is accounted by a *loss coefficient*, usually called *lambda* and is a fraction of dynamic head lost in the duct. Its magnitude is a function of only duct geometry and inlet swirl angle. However, apart from turbine exit ducts, most ducts (including intake duct) have constant inlet swirl angle of zero degrees, and hence λ is a function of the duct geometry alone.

1.0 Introduction

The performance of the ***THRUST ARCHITECTURE*** is significantly affected by the integration of the engine and its structure. The intake of gas turbine engine is an important component, which directly interfaces with the internal airflow of the engine and affects its performance characteristics. Since, the intake delivers the ambient air to the engine; the intake must be designed to provide an appropriate amount of the airflow to the engine for all load condition. Although the intake does no work on the flow itself, it is responsible for the quality of the air at the engine face, which requires high total pressure energy and minimum distortion at the aerodynamic interface plane (AIP).

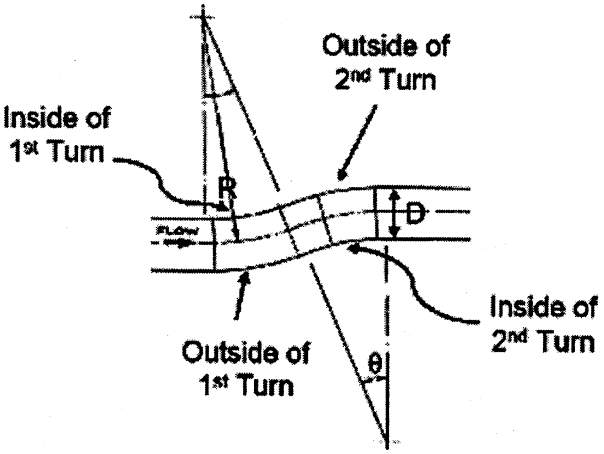

Fig. 2: A typical curved duct with two bends and showing a height offset.

Figure 2 shows a curved duct with two bends. In most curved ducts found in literature, we have observed that these ducts contain only two turns. This results in only a height offset and there is no overall change in flow direction, which would a specific feature of the duct used in the ***THRUST ARCHITECTURE***

The flow exiting the intake duct will enter the gas turbine engine and as discussed earlier, flow distortion at this stage would certainly affect the engine performance in several ways. Total pressure distortion, that is defined as DC(θ), is probably is widely studied form of inlet distortion. Other forms of inlet distortion that have been studied include total temperature distortion, planar waves and inlet flow angularity or swirl[8, 9, 10]. Total pressure distortion is generated by the shape of the duct in addition to the flow disturbances generated with transition in the cross-sectional shape along the length of the duct. Inlet swirl is known to effect engine performance in good as well as bad sense. Swirl, when generated in the same direction as compressor rotation, enhances engine performance stability. While, swirl rotating in a direction against the compressor rotation adversely affects the fan or compression system stability.

Gas turbine engine performance levels are generally quoted at ISO (International Organisation for Standardisation) and do not include effects of installation ducting (includes air intake and engine exhaust) pressure losses. This level of performance is termed as uninstalled and would normally be between inlet and exit planes consistent with engine manufacturer's supply. This includes from the flange at entry to the first compressor casing to the engine exhaust duct exit flange or to the propelling nozzle exit plane for the thrust engines. Later configuration is used for the 'THRUST concept'. Inlet guide vanes could be used to reduce the affect of inlet duct swirl (counter-swirl) or to enhance the affect of inlet duct swirl (co-swirl).

2 Intake Parameters

Intake is no different from any other existing engineering system where a fraction of the supplied energy goes waste i.e. it is spent in ways other than that is desired. An understanding of the process through which the energy is essential before a intake could be designed or merits/demerits of a design could be discussed. Following could be the probable source of losses in an intake-

- Friction on the walls of the duct
- Turbulent mixing and vortex generation
- Flow separation due to adverse pressure gradients as well as due to bends
- Flow distortion
- Shockwaves

Shock waves would not occur in the operating envelope of the intake as per the requirements of the ***THRUST ARCITECTURE.***. The remaining sources have varying levels of influence and would be discussed briefly in the following sections. Intake design could be divided into two parts. One, length and the shape of the intake and two, shape of the cross sections along the length. Since the shape and the length are decided by the ***THRUST ARCHITECTURE.***

we need to pay attention to the cross-sectional shape alone.

The Fig.3 shows a relationship between the total pressure loss and the duct length[17]. The losses are less in the short duct (when compared with a long one). The losses are even higher for a duct with curvature. The cause of this loss is the presence of a pressure gradient that exists between the inner and outer walls of a corner due to centrifugal forces. This causes the boundary layer from the outside of the first bend to move towards the inside causing some amount of swirl. However far greater amount of swirl is generated when flow separation occurs due to either lip separation or excessively steep bends.

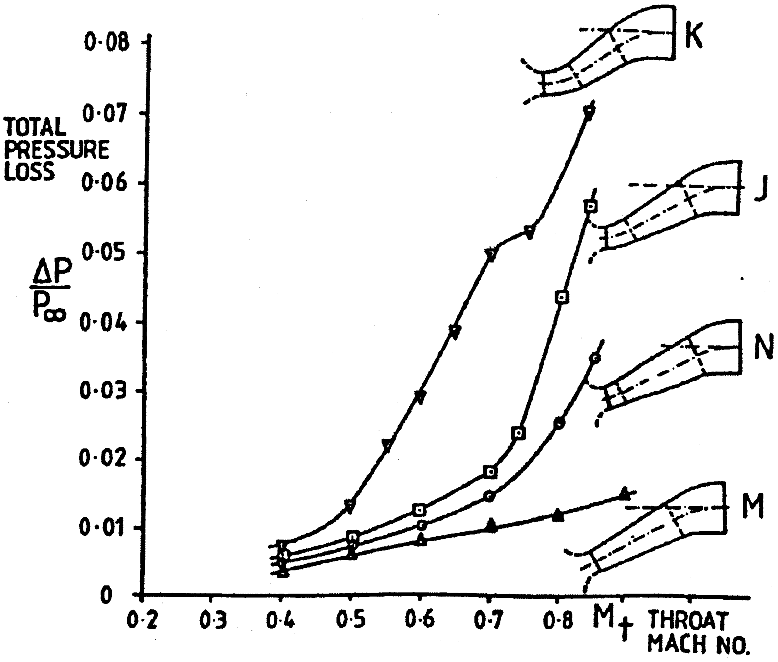

Fig. 3: Total pressure loss in a curved duct[17].

Air intake duct either diffuses *free stream* air from high inlet Mach number to a low Mach number (as in the case of aircraft cruising at high speed) or accelerates the *frees stream* air from static condition to acceptable level of compressor inlet Mach number (as in the case of land based power plant and aircraft takeoff). In either case the air stream suffers a total pressure loss through intake due to some or all of the reasons listed above. We would be discussing those effects of parameters in details. We can also write intake duct pressure in terms of following parameters only:

- Duct geometry- loss due to geometry is accounted by a *loss coefficient*, usually called *lambda*, λ
- Inlet Mach number or dynamic head
- Inlet swirl angle

Total pressure loss in terms of λ is defined as

$$P_{in} - P_{out} = \lambda . (P_{in} - PS_{in})$$

where,

P_{in} – total pressure at the entry to the duct

P_{out} – total pressure at the duct exit

PS_{in} – static pressure at the entry to the duct

The loss coefficient λ is the fraction of dynamic head lost in the duct, whatever the level of Mach number. Its magnitude is a function of only duct geometry and inlet swirl angle. However, apart from turbine exit ducts, most ducts (including intake duct) have constant inlet swirl angle of zero degrees, and hence λ is a function of only duct geometry. Once the intake duct geometry has been finalised and λ has been determined, the total pressure loss only varies with inlet dynamic head and hence Mach number. The value of λ for a given intake geometry is initially determined from experience, and by using commercially available corrections[11]. At a later stage of an engine project Perspex model may be tested in a rig test facility to validate these predictions.

An estimate of λ for preliminary analysis can be made by combining the building blocks listed below. If more than one of these features is used in series then the λ applies to the dynamic head entering each individual section:

- Large step contraction: λ=0.5 based on exit dynamic head. This value of λ can be reduced if a radius is employed at the point of contraction. (This condition will be encountered at the entry to the inlet in the thrust system design)

- Flow in a pipe of constant cross-sectional area:

$$\lambda = f\frac{L}{D}$$

where,

f – frictional factor, as found in 'Moody chart'[12]

L- duct length (m)

D- hydraulic diameter (m)

- Conical nozzles: λ is between 0.15 to 0.2 for cone angles between 15° and 40° depending upon the area ratio. (This condition may be encountered near the entry, bends and exit of intake duct depending on the design)

Total pressure loss with respect to inlet Mach number can be determined initially by expressing inlet dynamic head divided by inlet total pressure as a function of inlet total to static pressure ratio. Rig test data of total pressure loss in the intake should be generated for operational Mach number range.

2.1 Pressure Recovery

In the design of traditional turbojet and turbofan intakes, pressure recovery (PR) is a commonly used parameter to measures the efficiency with which the intake delivers the air from ambient static pressure to a desired AIP static pressure. It is defined as the ratio of the total pressure at the AIP to that at upstream infinity.

$$\eta_{PR} = \frac{P_2}{P_0}$$

Pressure recovery is affected by two loss sources viz. skin friction and turbulent mixing (section 2). Pressure recovery is a measure of loss in the intake flow with respect to the isentropic flow. Since, total pressure could be obtained easily form the experimental setup, therefore the performance of the intake duct design could be determined *a-priori* before integrating it to the engine. The effect of intake pressure loss on engine thrust depends on the characteristics of the engine. Intake pressure loss can be assumed to be translated directly to engine thrust by the following relationship[13]:

$$X = K\frac{\Delta P}{P_0}$$

where,

ΔX- loss in thrust

X- thrust

K- a factor depends on the type of engine; generally $1<K\sim1.5$

ΔP- total pressure loss at the intake exit

P_0 - fee stream total pressure

For flow speeds in the range of Mach number 0.5 to 1, the above equation can be roughly approximated to

$$X = 0.35KM_0\frac{\Delta P}{q},$$

where M_0 is free stream Mach number and q is free stream dynamic pressure.

It is evident from the above equations that the loss in engine thrust is almost directly proportional to the intake pressure loss. Since the engine manufacturer will quote only the uninstalled engine performance level at the time of supply, hence the exact amount of intake loss should be known before selection of an engine for a given thrust requirement for the ***THRUST ARCHITECTURE.***

2.2 Distortion

Total pressure distribution at the engine face is one of the parameter that contributes to the intake losses[13]. The distortion can be either steady or time varying and is a significant cause of premature engine surge[§] as well as buzz. The type of distortion (surge or buzz) may cause a range of undesirable effects such as asymmetric loading of the compressor

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[§] Engine surge is caused by stalling of the compressor blades and can result in reverse flow resulting in a dramatic reduction in the engine thrust.

blades. The distortion is calculated in terms of distortion coefficient and is calculated at the intake exit cross section (or at AIP) as follows-

$$DC(\phi,\psi)=\frac{P_0 - P_0(\phi,\psi)}{q}, 0 < \phi < 2\pi$$

where P_0 is the total pressure, q is the dynamic pressure and ϕ is the starting angle for a pie segment of angle ψ of the intake exit and are given as follows-

$$P_0 = \frac{\int_0^{2\pi}\int_0^{R} P_0(r,\theta)\, r\, dr\, d\theta}{\int_A dA}$$

$$P_0(\phi,\psi) = \frac{\int_0^{\psi}\int_0^{R} P_0(r,\phi+\theta)\, r\, dr\, d\theta}{\int_\phi dA}$$

$$q = \frac{\int_A q\, dA}{\int_A dA}$$

All kind of intake distortions are felt at the aerodynamic interface plane (AIP) and would severely affect the compressor performance. Figure 4 shows a typical compressor map along with the stability margin where a dotted line indicates the stability line. At this line compressor operation is no longer stable due to a phenomenon known as surge. The stability margin could be defined as follows-

$$SM = \frac{PR_{SL} - PR_{OP}}{PR_{OP}} \times 100$$

where PR_{SL} is the pressure ratio at the stability limit and PR_{OP} is pressure ratio at the operating point. Figure 5 and Table 1 show some of the factors affecting the stability margin of a compression system. The steady state total pressure distortion has been found to affect both the operating line (increase) and the stability line (decrease), reducing the overall stability margin for the compression system.

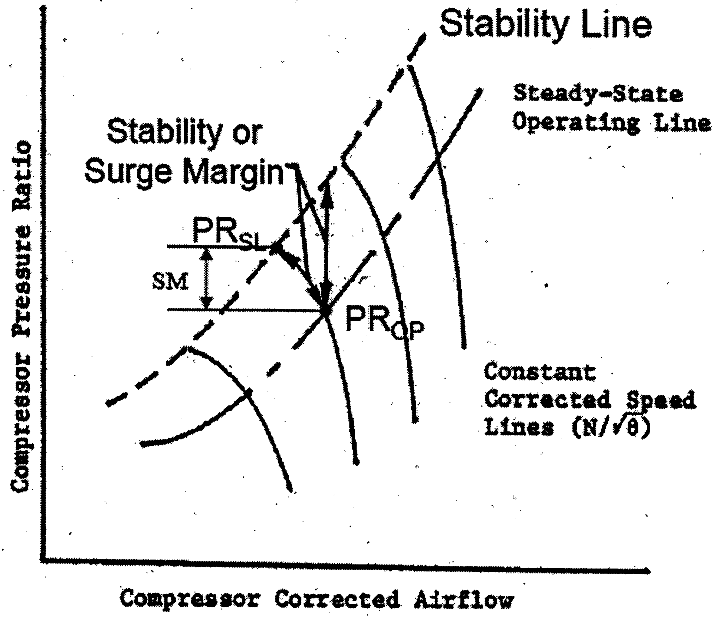

Fig. 4: A Typical compressor map with the stability margin[14].

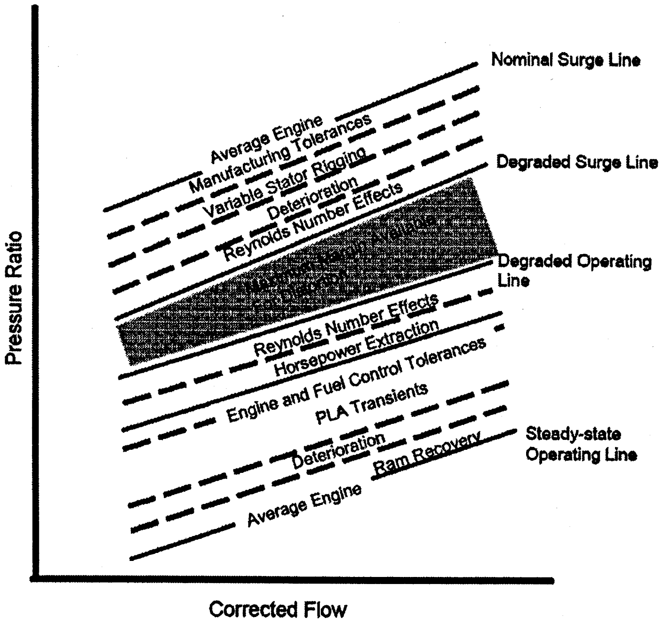

Figure 1.6 Factors Affecting Compressor Stability Margin (taken from AIR 1419, 1983)

Fig. 5: Factors affecting compressor stability margin[15].

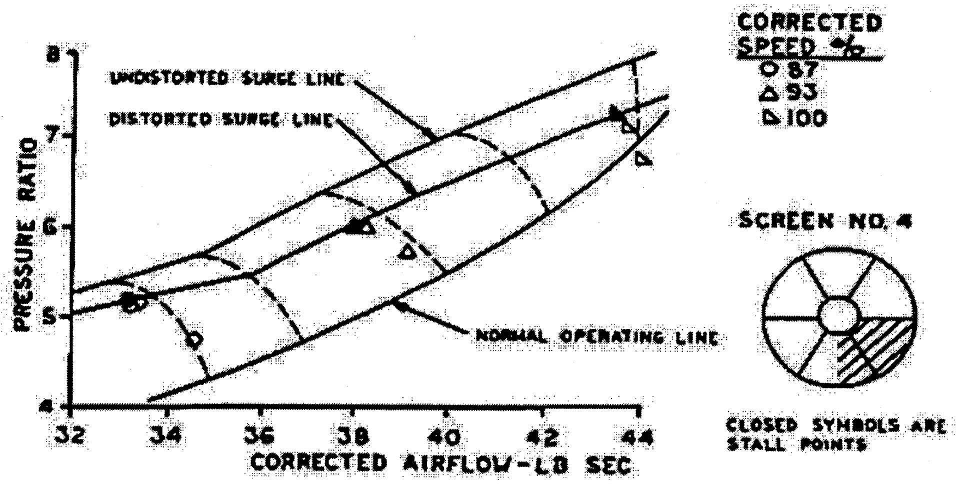

Fig. 6: Distorted speed line for the circumferential distortion[14].

In Fig. 6 results are presented form engine testing showing the change in operating point for distorted flow compared to undistorted flow. It clearly shows various total pressure distortions (see table 1) move the constant speed line to a lower position on the compressor map. The distorted flow operating point for the same corrected rotor speed is seen to move off the undistorted flow speed line.

Table 1: Various types of distortions affecting compressor stability margin[15].

Type of distortion	Operating line	Surge line
Steady state total pressure distortion	X	X
Temperature distortion	X	X
Swirl distortion	X	X
Max instantaneous total pressure distortion		X

2.3 Swirl

Swirl represents a form of energy loss, as the energy is used in accelerating the flow in the angular direction and does not contribute to engine thrust. Inside a curved intake, the swirl is caused by the shape of the duct itself. Along with various distortions as discussed in the previous section, swirl is also responsible for the non-optimal compressor operation. Defining the "swirl coefficient", SC(θ) as the maximum average circumferential component of cross-flow velocity in a θ° sector of the measuring station non-dimensionalized by dividing by the mean throat velocity. Figure 7 shows the development of swirl (and distortion) coefficient with a curved intake incidence. It is quite evident that swirl (and distortion) generation does not start to occur until the angle of incidence exceeds just over 10°. In the absence of any other data, this generic curved intake data could be used as a design guideline. As far as intake for ***THRUST***

ARCHITECTURE is concerned, we need to worry about the effect on incidence on distortion coefficient and swirl as this is going to be fixed.

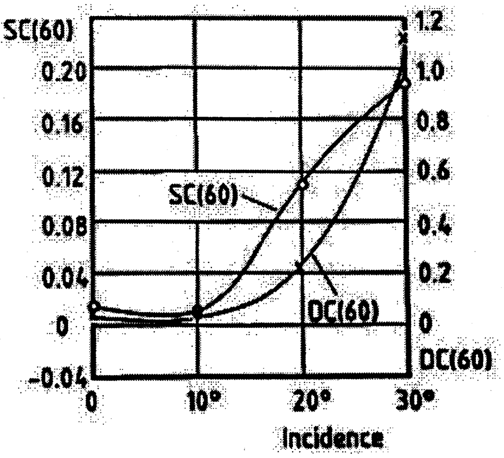

Fig. 7: Variation of swirl and distortion in a curved intake[16].

It can clearly be seen from Fig. 8 that at zero incidence a curved duct creates swirl at AIP. The pictures become quite clear if one looks at the pressure plot in the right. There is a huge variation in the pressure distribution between the inner and outer sides (see Fig. 2 for the geometry, also Fig. 8). The trend gets inverted after the bend indicating that after the first bend the swirl is small and is directed from inside to outside. At the second bend, the pressure gradient changes its direction and it introduces the swirl in the opposite direction.

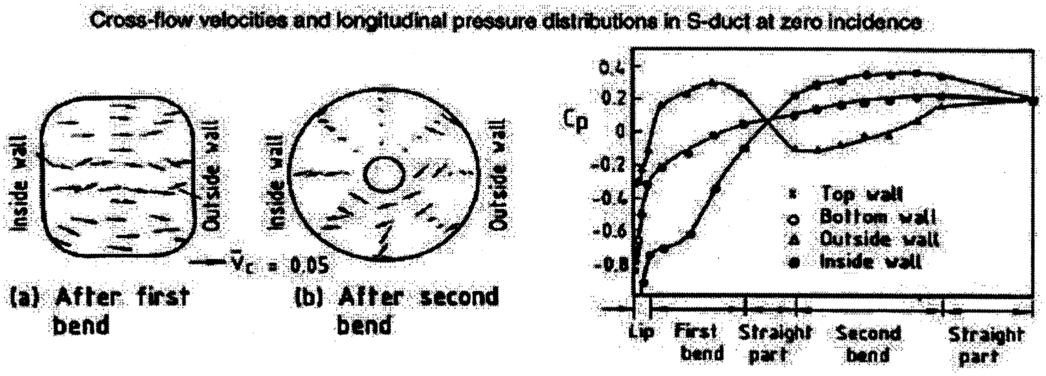
Cross-flow velocities and longitudinal pressure distributions in S-duct at zero incidence

Fig. 8: Swirl generation (left) and longitudinal pressure distribution (right) in a curved duct at zero incidence[13].

3.0 Engine Design considerations

3.1 Intake mouth and lip design

The intake as an aerodynamic duct 'captures' a certain stream tube of air, thus dividing the air stream into an internal flow and an external flow, as indicated in fig. 8. Internal flow feeds the engine with required mass flow while external flow influences the aerodynamics of the engine frame. The basic shape of the duct is important to ensure air supply to the engine at a moderate subsonic speed of Mach 0.4-0.6 (most of the compressors are designed at this speed range). Principle stations in the flow are: station '0' represents free stream flow, station '1' at the duct entry and station '2' at the engine face. Area at engine face, A_2, is fixed by the engine size while entry area, A_1, is a first item of choice for the intake designer. Further such selection relate to the shape of the duct walls both internally and externally.

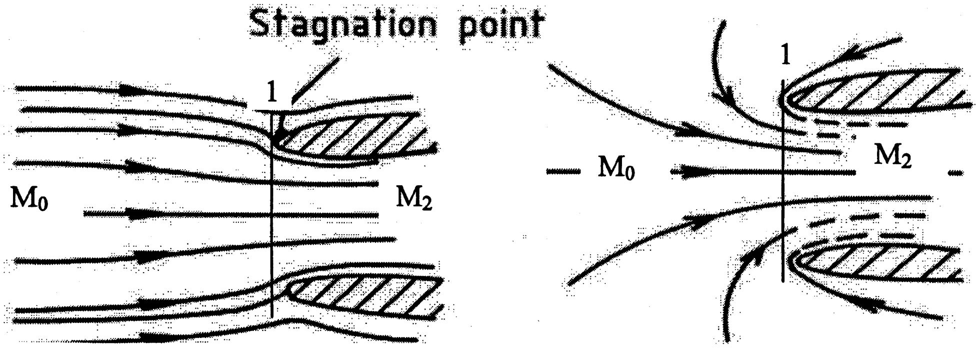

Fig. 9: Air flow through intake[13] with a forward speed M_0 (**left**) and for static condition (**right**).

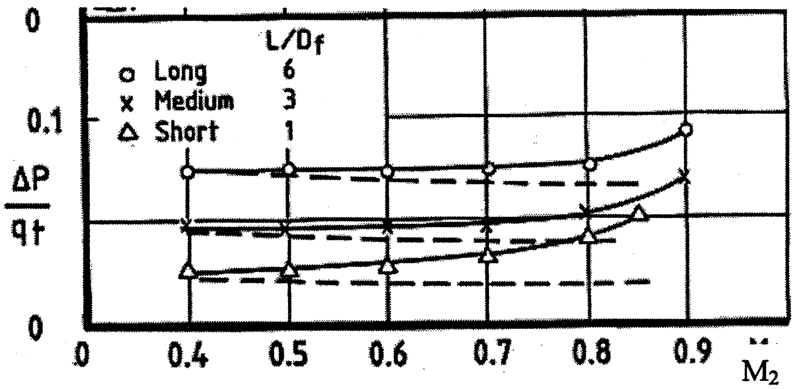

Fig. 10: Effect of intake opening and Mach number on total pressure loss[13].

Since the air intake of the **THRUST** system will operate under static ground conditions, the air flow behavior will be similar to as shown in Fig. 9 (right). Under these conditions air is drawn from all directions, so that A_0 becomes effectively infinite. Now the entry flow Mach number will depend on the ratio of A_0 and A_1 and a high Mach number at the station 2 under such conditions will increase total pressure loss through the intake duct as shown in Fig. 10. The figure shows total pressure loss as a function of Mach number, as achieved at the entry (throat), and for different sizes (L/D) of intake duct.

One important design parameter called, lip shape should also be considered for overall performance evaluation of intake duct. Fig. 11 shows variation of total pressure loss with respect to throat Mach number and capture flow ratio (A_0/A_1) for sharp lip and elliptic lip. It is evident from the plot that, when compared to a sharp lip, an elliptic lip performs better in terms of the total pressure loss.

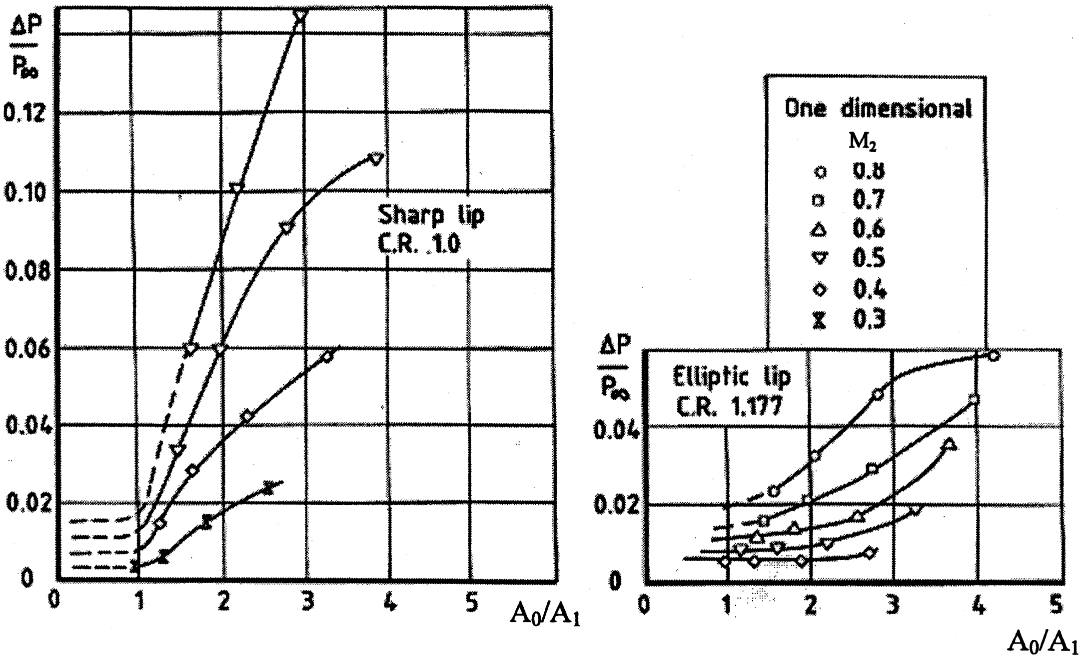

Fig. 11: Influence of throat Mach number and capture flow ratio on total pressure loss[13].

The intake shown in Fig. 9 (right) is also known as a "bell mouth" intake. An ideal configuration of such an intake would be where the radius of curvature increases toward the throat direction (see Fig. 12). Since an intake is employed in the **THRUST** architecture under static ground condition, a converging duct would be more appropriate as against diverging aircraft engine intake ducts. Thus, selection of a bell mouth with well defined elliptic lip shape would be the best choice for the **THRUST** concept. It can be designed to feed all engines together by dividing the exit of bell mouth intake by the same numbers as the engines. However, intake design should ensure that the Mach number at the engine face should be within the acceptable range (0.4M-0.6M, depending on the engine requirement) under all operating conditions.

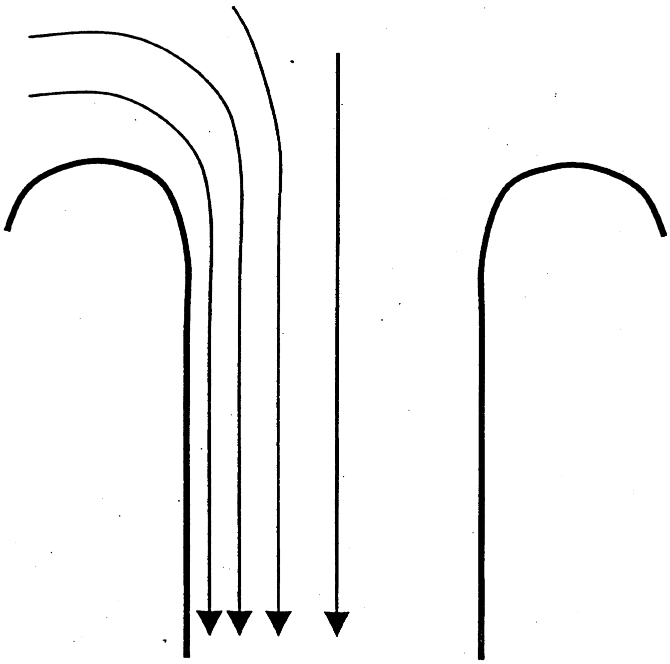

Fig. 12: A schematic diagram of a bell-shaped entry of an intake.

3.2 Cross section shaping

The purpose of this section is to discuss the factors that influence the cross-sectional shape of the intake duct. As we have discussed in section 2, we note that there are two main sources of losses and those could be attributed to cross-sectional shaping, namely: Skin friction drag and losses due to the introduction of non-axial flow velocity components due to streamwise vortices. One thing that clearly emerges out of the discussion is that if somehow we could minimize the surface area to minimize losses due to skin friction, while maintaining the correct area profile. One can achieve this only with a shape with minimum hydraulic diameter. Clearly, the shape with minimum hydraulic diameter is a circle, thus the optimum aerodynamic cross section has to be circular in shape.

Though a circular duct cross-section is the ideal, however, coming to this conclusion, and that also so quickly, would be an over-simplification of things. There are other design factors and they all would, somehow, take us away from the optimal circular shape. Still, the design driver would be the hydraulic diameter. An important parameter affecting the hydraulic diameter of any shape is the aspect ratio – the ratio of major to minor axis. In order to reduce the losses resulting from their generation of streamwise vortices, all bends must be smoothened. There is also a need to pay attention on internal angles – these angles should not be too small. This also has the effect of lowering the perimeter-to-area ratio mentioned above. At this stage where we are discussing the cross-sectional shaping, it is quite pertinent to highlight the link between external and internal shaping. Internal shaping of an intake duct is driven primarily by aerodynamic considerations, while external shaping, on the other hand is driven by airframe integration considerations. However, despite very different core design drivers, there is a strong cross coupling of the two, which arises from their necessary proximity in most installations. It is impractical to have a highly aerodynamically efficient duct that cannot be integrated with an existing engine. Another point that needs due consideration during the intake design is integrating non-circular forward section of the intake with the circular section at the AIP. These two sections must be blended smoothly. We would be requiring a CAD software to design and draft the blending of cross-sectional shapes accurately while maintaining the area profile.

3.3 Bend design

Research's shown that the first bend itself is a primary source of losses and engine face flow distortion in a curved intake[17]. By increasing the curvature ratio of the first bend and by introducing a straight duct between first and second bend, one could obtain a significant improvement in the pressure recovery at the AIP (see Fig. 1). Recent studies[18] have shown that introduction of a straight portion between two bends does not necessarily improve the performance of a curved duct in terms of overall pressure recovery and distortion/swirl when the axes of inlet and exit planes are aligned in the same direction. Most of the curved ducts studied had only two bends whereas intake required for the THRUST concept would have only one single bend as depicted in figure 1.

However, it should be ensured that the generation of swirl due to duct curvature as total pressure and cross-flow losses causing the danger of engine surge. However, before getting into how to control swirl and minimize undesired effects, we should be looking into the mechanism of swirl generation to gain more in-depth understanding. Swirl generation in ducts with bends is caused by two factors viz. the centrifugal pressure gradient at the first corner and the presence of flow separation from a source independent of the bend itself. It is the interaction between the centrifugal pressure gradient and a low energy region associated with flow separation which causes the most severe swirl generation.

Having established the causes of distortion/swirl generation in curved ducts, our job, now, would be to ensure that the distortion/swirl should be minimized through some design guidelines. In section 2.3, we have discussed the reasons behind swirl generation. From the arguments, and results shown in Fig. 1, we infer that any two bends should be far from each other, at least far enough so that flow separation caused by the first bend dies down before it reaches to the next bend. From experiments, Guo *et. al.*[16] determined that a spoiler consisting of a vertical strip projecting 13% of the entry width from the inside lip would reduce the swirl to zero. A second method for swirl control is the addition of a fence to control the flow around the first bend. Researches indicate that the best performing fence would be that is positioned on the outside wall, with a length approximately 75% of the bend length and with a leading edge positioned between 20% to 40% of bend length behind the intake lip.

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