Design Solutions to Curved Air Intake for Turbojet Engines Incorporated Into the THRUST ARCHITECTURE

Abstract

In a previous paper the major design parameters were identified, which should be considered in the design of the curved turbojet intake. In that paper it was pointed out that the curved intake (Figure 1) air inlet that typically results in pressure drops could be overcome or designed to become significantly small or non-existent for all practical purposes.

In that paper we identified and discussed the following parameters that would be related to the intake duct:

1. Inlet Flow Angularity or Swirl
2. Shockwaves
3. Duct Length
4. Flow Distortion

1.0 Introduction

The purpose of this paper is to address design considerations that should be considered such that these parameters would have minimal, if any, impact on performance. In addition, “bend design” and “pressure recovery” considerations are addressed, which in the final phase of these considerations would be optimized using technical design engineering software. The pressure losses (if any) would be caused by the presence of a pressure gradient that exists between the inner and outer walls of a corner due to centrifugal forces.

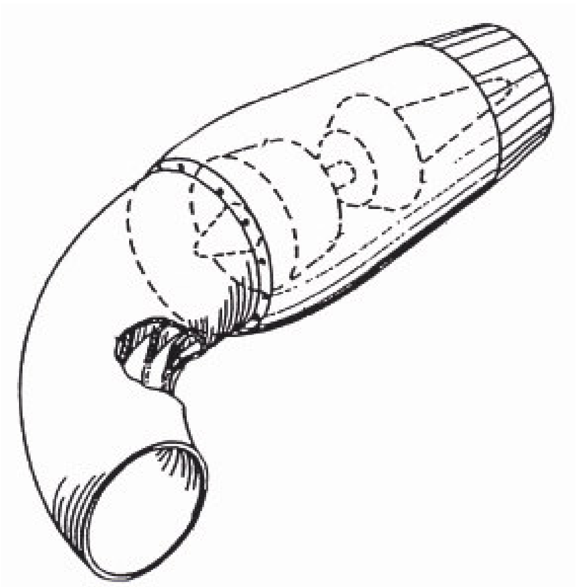

Figure 1: Curved air intake extender with engine.

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.

2.1 Curved Intake Solutions

Figure 2 shows a curved intake as it is installed on the L1011 and the Boeing 727. In these two cases, the intake has two bends with a fairly straight portion in the middle. There are several design considerations posed by these curved intakes. Flow from the intake duct is not of an acceptable flow quality that could be admitted. The flow must be controlled or corrected to improve the flow quality entering the engine. Several different aspects of duct flow have been studied in the past and are available in the literature [3,4,5,6,7,8,9] examining the nature of the flow development within a curved duct that is often diffusing. It includes the effects of the degree of turning (i.e. bends), diffusing cross-sectional area (exit to entry area ratio), and transitioning cross-sectional area (continuous change in cross-sectional shape).

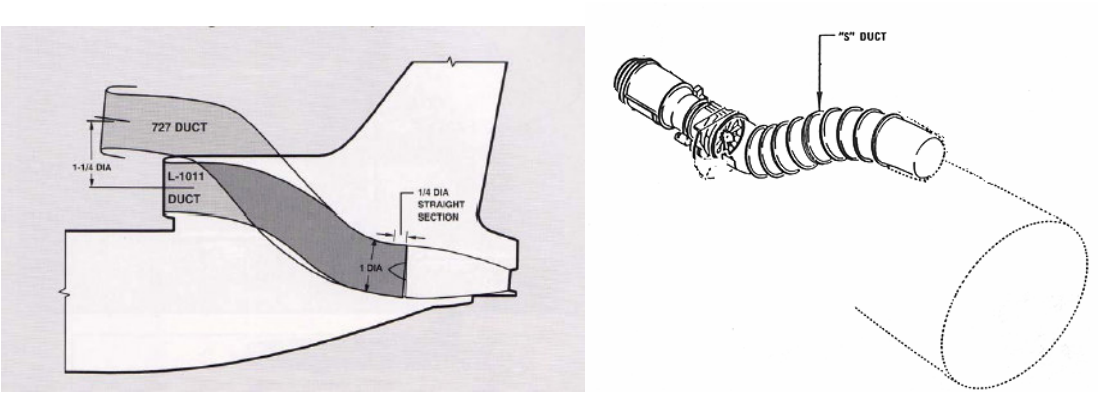

Figure 2: Curved duct configurations [1, 2].

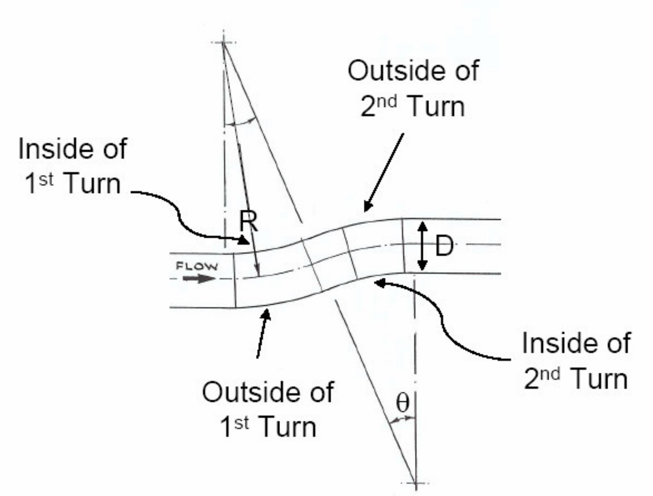

Figure 3: A typical curved duct with two bends and showing a height offset.

Figure 3 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 be a specific advantage of the duct used in the ***THRUST ARCHITECTURE***.

The flow exiting the intake duct will enter the turbojet engine and as discussed in a previous paper *Design solutions to Curved Air Intake for Turbojet Engines Incorporated into the* ***THRUST ARCHITECTURE,*** will yield flow distortion and at this stage would affect engine performance, although the effects can be corrected. Total pressure distortion, that is defined as DC(Θ), is a widely studied form inlet distortion. Other forms of inlet distortion that have been studied include total temperature distortion, planar waves, and inlet flow angularity or swirl [10], [11], [12]. Total pressure distortion is generated by the shape of the duct in addition to the flow disturbances generated within the transition in the cross-sectional shape along the length of the duct. **Inlet Swirl, when generated in the same direction of compressor rotation enhances engine performance stability,** while Swirl rotating in a direction against compressor rotation adversely affects the fan or compression system stability.

2.2 Swirl

It was pointed out in the paper *Air Intake Parameters and Their Minimization to Curved Air Intake for Turbojet Engines* that 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 4 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.

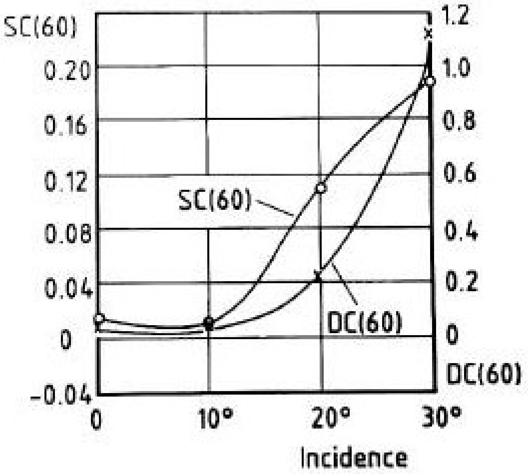

Figure 4: Variation of swirl and distortion in a curved intake[11].

It can clearly be seen from Figure 5 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 Figure 3 for the geometry; also Figure 5). The trend gets inverted after the bend, indicating that after the first bend the swirl is small and is directed form inside to outside. At the second bend, the pressure gradient changes its direction and it introduces the swirl in the opposite direction.

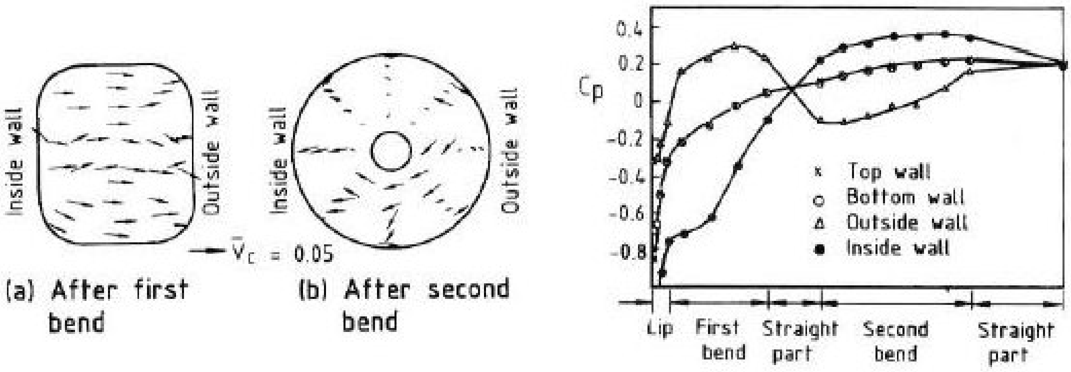

Figure 5: Swirl generation (left) and longitudinal pressure distribution (right) in a curved duct at zero incidence [10].

As far as air intake as it related to the ***THRUST ARCHITECTURE***, this concern can be eliminated since the incidence on distortion coefficient can be corrected.

2.3 Intake Mouth and Lip Design

One important design parameter called lip shape should also be considered for overall performance evaluation of intake duct. Figure 6 shows a variation of the 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 an elliptic lip be favored with respect to sharp lip as it produces low total pressure loss. The intake shown Figure 8 is also known as a "Bell Mouth" intake. An ideal Configuration of such an intake would be where the radius of curvature increases towards the throat direction. Thus selection of a Bell Mouth with well defined elliptic lip Shape would be the best choice for the **THRUST ARCHITECTURE.** This is to say that an elliptic lip performs better in terms of total pressure loss. However, the intake design should ensure that the Mach number at the engine face should be within the acceptable range (0.4M-0.6M) under all operations.

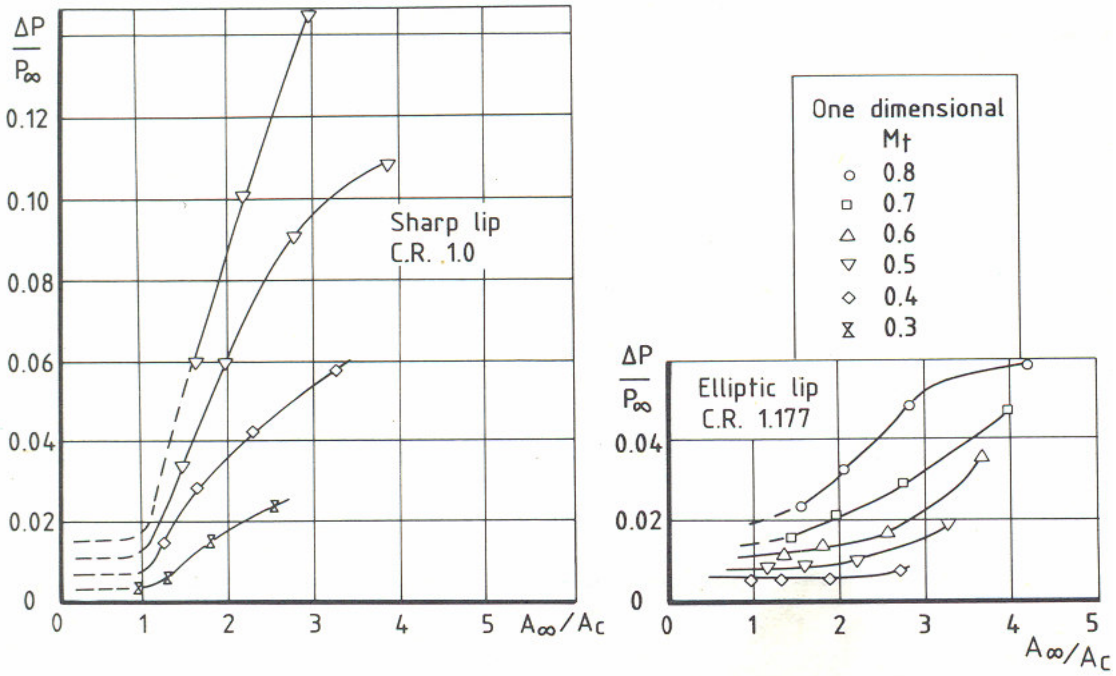

Figure 6: Influence of throat Mach number and capture flow ratio on total pressure loss [10].

The intake shown in figure 7 (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 figure 9).

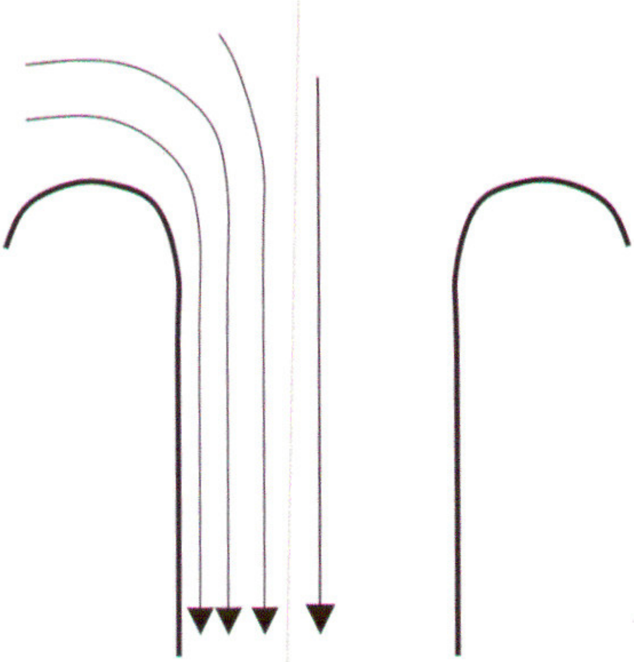

Fig. *9* **:** A schematic diagram of a bell-shaped entry of an intake.

Since an intake is employed in the **THRUST ARCHITECTURE** under static ground condition, a converging duct would be more appropriate as against diverging aircraft intake ducts. Thus, the air flow behavior will be similar to as shown in Figure 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 Figure 8. 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.

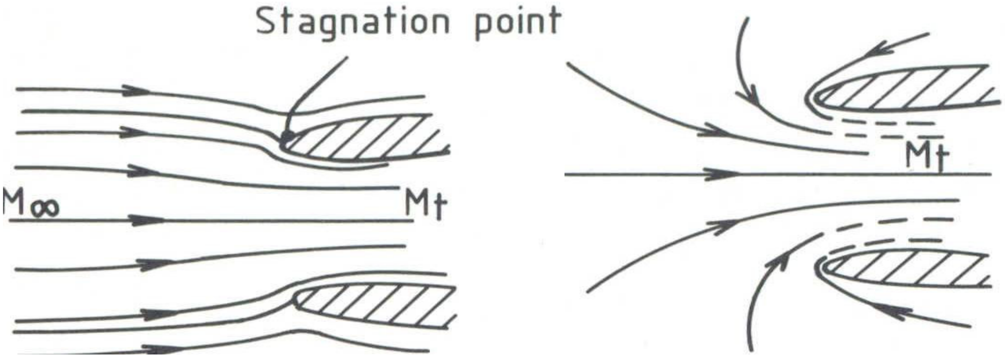

Figure 7: Air flow through intake[15] with a forward speed M_0 (left) and for static condition (right).

2.4 Cross Section Shaping

The purpose of this section is to discuss the factors that influence the cross-sectional shape of the intake duct. 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 if somehow we could minimize the surface area to minimize losses due to skin friction, while maintaining the correct area profile skin friction drag and loss would be at almost undetectable levels. 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.

A circular duct cross-section may be thought of as an 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 the cross-sectional shaping is being discussed, 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 the non-circular forward section of the intake with the circular section at the AIP. These two sections must be blended smoothly. We will require a CAD software to design and draft the blending of cross-sectional shapes accurately while maintaining the area profile.

2.5 Bend Design

Research has shown that the first bend itself is a primary source of losses and engines face flow distortion in a curved intake[12]. 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 Figure 1). Recent studies[13] 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. As per the ***THRUST ARCHITECTURE*** design, it is necessary that the intake turn through some combination of bends so the desired amount of air could be fed into the engine. Most of the curved ducts studied had only two bends, whereas intake required for the ***THRUST ARCHITECTURE*** would have only one bend as depicted in Figure 1.

However, it should be noted that the generation of swirl is 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 look 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, is to ensure that the distortion/swirl should be minimized through some design guidelines. In the section related Swirl, the reasons behind swirl generation were discussed. From the arguments and the results shown in Figure 7, 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.[11] 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.

2.6 Intake Design Considerations and Performance Enhancements

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 Figure 7. 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. The area at the 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 selections relate to the shape of the duct walls both internally and externally.

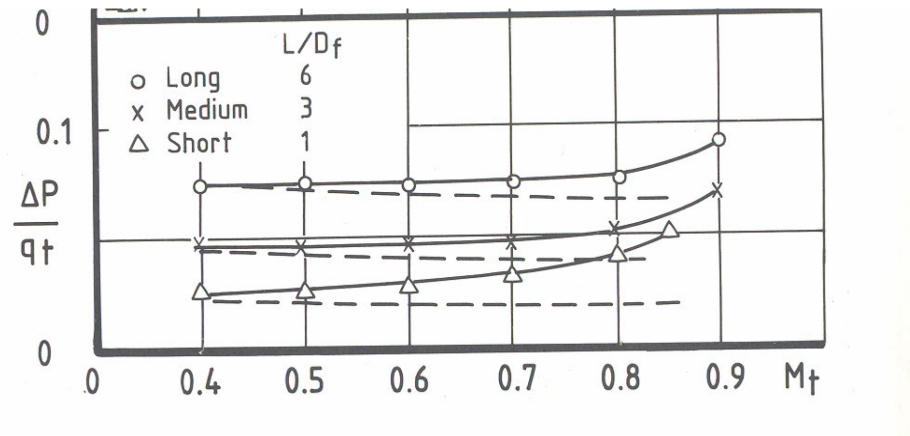

Figure 8: Effect of intake opening and Mach number on total pressure loss[10].

Since the air intake of the ***THRUST ARCHITECTURE*** system will operate under static ground conditions, the air flow behavior will be similar to that shown in Figure 7 (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 entry under such conditions will increase total pressure loss through the intake duct as shown in Figure 8. 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.

2.7 Pressure Recovery

In the design of the traditional turbojet and turbofan intakes, pressure recovery (PR) is a commonly used parameter to measure 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. Pressure recovery is a measure of loss in the intake flow with respect to the isentropic flow. Since total pressure could be obtained easily from the experimental setup, the performance of the intake duct design could be determined *a-priori* before integrating it to the engine. The effect of the 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[10].

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

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

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

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* concept.

Gas turbine engine performance levels are generally quoted at ISO (International Organization for Standardization) 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 the inlet and exit planes, consistent with engine manufacturer's supply. This includes from the flange at the entry to the first compressor casing to the engine exhaust duct exit flange or to the propelling nozzle exit plane for the engines. Later configuration is used for the *THRUST ARCHITECTURE* 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).

It is hoped that this paper *Design Solutions to Curved Air Intake for Turbojet Engines Incorporated Into the THRUST ARCHITECTURE* and the previous paper *Curved Air Intake Parameters and Their Optimization for Turbojet Engines Incorporated Into the* ***THRUST ARCHITECTURE*** will offer insight into this design phenomena.

References

[1] Upton, J. (2001). Lockheed L-1011 *Tristar, 8*. Airliner Tech Series. Specialty Press Publishers and Wholesalers.

[2] *Aircraft and power plant corner website*. Retrieved March 2004 from http://home.swipnet.se/~w65189/transport_aircraft/b727/boeing_727_series.htm

[3] Kramer, J., & Stanitz, J.D. (1952). *Two-dimensional shear flow in a 90° elbow*. NACA Technical Note 2736, Lewis Flight Propulsion Laboratory.

[4] Rowe, M. (1970). Measurements and computations of flow in pipe bends. *Journal of Fluid Mechanics,43*, Part 4, 771-783.

[5] Bansod, P., & Bradshaw, P. (1972). The flow in s-shaped ducts. *The Aeronautical Quarterly, 23*.

[6] Vakili, A., Wu, J.M., Liver, P., & Bhat, M.K. (1983). *An experimental investigation of secondary flows in an s-shaped circular duct*, NASA Final Report NAG3-233.

[7] Taylor, A.M.K.P., Whitelaw, J.H., & Yianneskis, M. (1984). *Developing flow in s shaped ducts II – Circular Cross-Section Duct.* NASA Contractor Report 3759.

[8] Povinelli, L.A., & Towne, C.E. (1986). *Viscous analyses for flow through subsonic and supersonic intakes.* AGARD Propulsion and Energetics Panel Meeting on Engine Response to Distorted Inflow Conditions.

[9] Sullivan, J.P., Murthy, S.N.B., Davis. R., & Hong, S. (1982). *S-shaped duct flows.* Office of Naval Research Contract Number N-78-C-0710.

[10] Seddon, J., & Goldsmith, E.L. (1999). *Intake aerodynamics* (2nd ed.). Oxford: Blackwell Science Ltd.

[11] Guo, R.W., & Seddon, J. (1983). The swirl in an s-duct inlet of typical air intake proportions. *Aeronautical quarterly.*

[12] Goldsmith, E.L. (1988). *Subsonic air intake: Weapon aerodynamics*. Royal Aeronautical Society.

[13] Yu, S.C., & Chan, W.K. (October 1996). Effect of a central straight on an s-shaped diffusing duct. *Aeronautical Journal*, Paper No. 2182.