Curved Air Intake Parameters and Their Optimization for Turbojet Engines Incorporated into the THRUST Architecture

Abstract

Proper air intake design in required to insure that a turbojet engine is properly supplied with sufficient air under all conditions of operation. It is generally well known that the curved intake might result in pressure loss; however, the ***THRUST ARCHITECTURE*** anticipated this loss in pressure and incorporated a solution to this phenomena 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 the ingestion of unwanted external physical debris that might result in engine failure or damage. The geometry of the intake's optimum performance is related to what is generally well known as a loss coefficient, typically identified by Greek letter lambda (λ) which represents the fraction of the dynamic head lost in the duct. This loss can be easily corrected or compensated for by proper design of the inlet duct.

1. Introduction

The performance of the ***THRUST ARCHITECTURE*** is affected by the integration of the turbojet engines into this architecture. The intake of air into the turbojet is therefore a very important component which directly interfaces with the internal airflow to the engine and therefore 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 airflow to the engine to accommodate various load conditions. Although the intake does no work on the flow itself, it is responsible for the quality of the air at the engine interface, which requires high total pressure energy and minimum distortion at the Aerodynamic Interface Plane (AIP). It is evident that from the ***THRUST AIRCHTECTURE*** engine intake extensions that the intake, when incorporated as an integral part, would not be of conventional design but contains the necessary inlet air vanes to approach optimum air flow. The actual bend and internal vane settings would be optimized using computer software to obtain the maximum uniform flow and minimize the value of lambda (λ).

2.0 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 an intake could be designed or merits/demerits of a design could be discussed.

2.1 Inlet Flow Angularity or Swirl

Swirl represents a form of energy loss, as the energy is used in accelerating this 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, swirl is responsible for the non-optimal compressor operation. Defining the "swirl coefficient," $SC(\theta)$ as the maximum average circumferential component of cross-flow velocity in a $\theta°$ sector of the measuring station non-dimensionalized by dividing by the mean throat velocity. It is pointed out 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.

The engines are preferably turbojets, (note figure 1) having a compression stage, a combustion stage, and a turbine stage to drive the compressor. Power is provided by the thrust of the expanded gas as it leaves the engine exhaust.

The air conduit beads 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 turbojet may be releasably connected to the extremity of a support arm by the provision of a mounting saddle having thrust mounting blocks and a plurality of circumferential mounting collars.

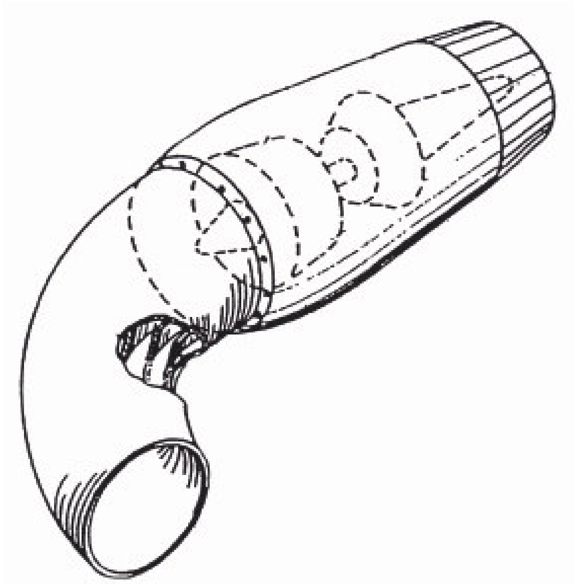

Figure 1: Curved air intake extender with engine.

2.2 Shockwaves

A shockwave is a type of propagating disturbance and is characterized by a sudden change in the characteristics of the medium such as pressure, temperature, and speed. What is generally referred to as shockwave compression can impact the pressure**.** Shock waves would not occur in the operating envelope of the intake as per the requirements of the ***THRUST ARCHITECTURE***. The remaining sources have varying levels of influence and will be discussed briefly in the following sections. Intake design could be divided into two parts: (1) length and the shape of the intake; and (2) 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 only to the cross-sectional shape.

2.3 Duct Length

Figure 2 shows a relationship between the total pressure loss and the duct length[1]. 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, a far greater amount of swirl is generated when flow separation occurs due to either lip separation or excessively steep bends.

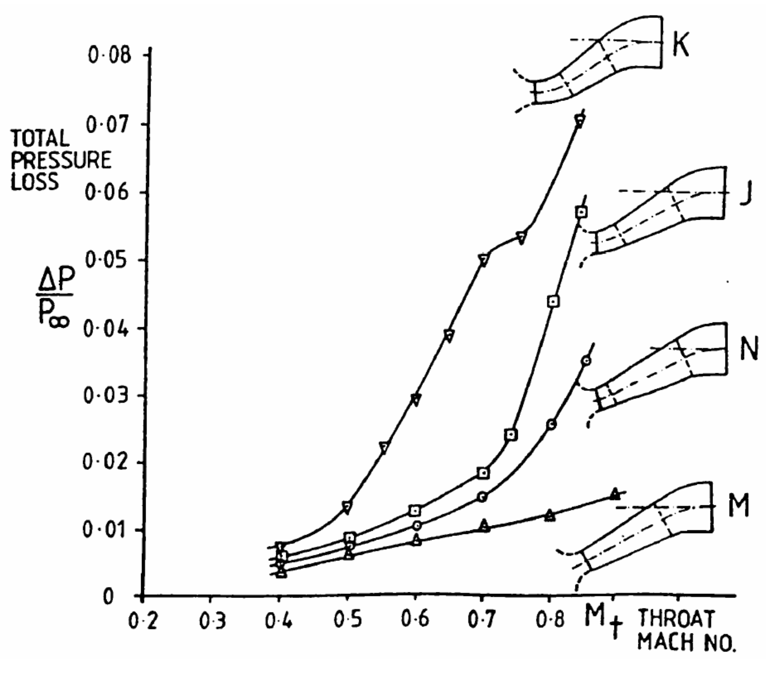

Figure 2: Total pressure loss in a curved duct[1].

The air intake duct either diffuses free stream air from a high inlet Mach number to a low Mach number (as in the case of aircraft cruising at high speed), or accelerates the *free stream* air from static condition to an 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 will be discussing those effects of parameters in detail. Intake duct pressure can only be written in terms of following parameters:

- Duct geometry – loss due to geometry is accounted by a loss coefficient, usually called lambda, λ.
- Inlet Mach number of 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 ducts) have a constant inlet swirl angle of zero degrees, and hence λ is a function of only duct geometry. Once the intake duct geometry has been finalized 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[4]. At a later stage of an engine project the 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: $\lambda = 0.5$ 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 ARCHITECTURE*** design.)
- Flow in a pipe of constant cross-sectional area:

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

where,

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

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

2.4 Distortion

Total pressure distribution at the engine face is one of the parameters that contribute to the intake losses[15]. 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 blades. The distortion is calculated in terms of the 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 kinds of intake distortions are felt at the aerodynamic interface plane (AIP) and would severely affect the compressor performance. Figure 3 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 –

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

§ 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.

where PR_{SL} is the pressure ratio at the stability limit and PR_{OP} is the pressure ratio at the operating point. Figure 4 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.

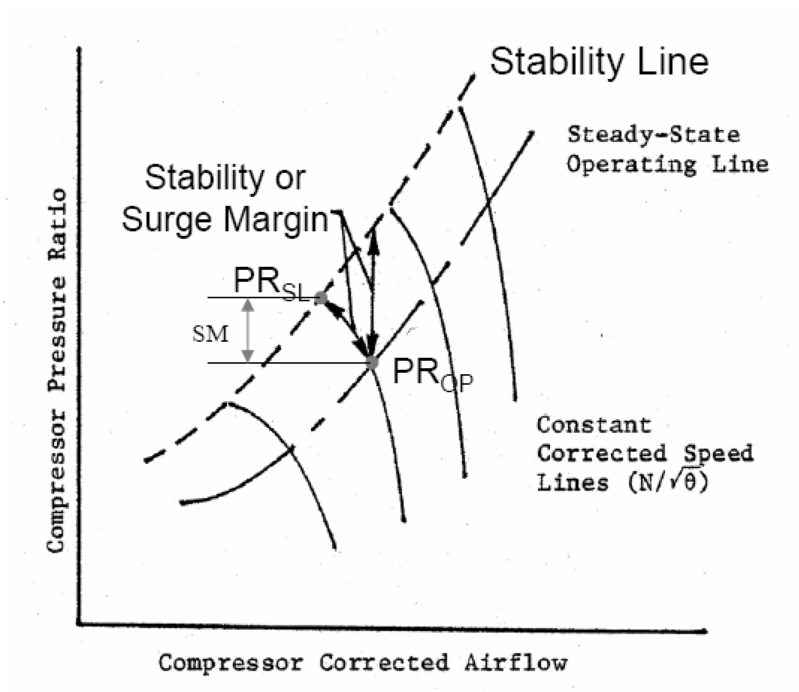

Figure 3: A typical compressor map with the stability margin [2].

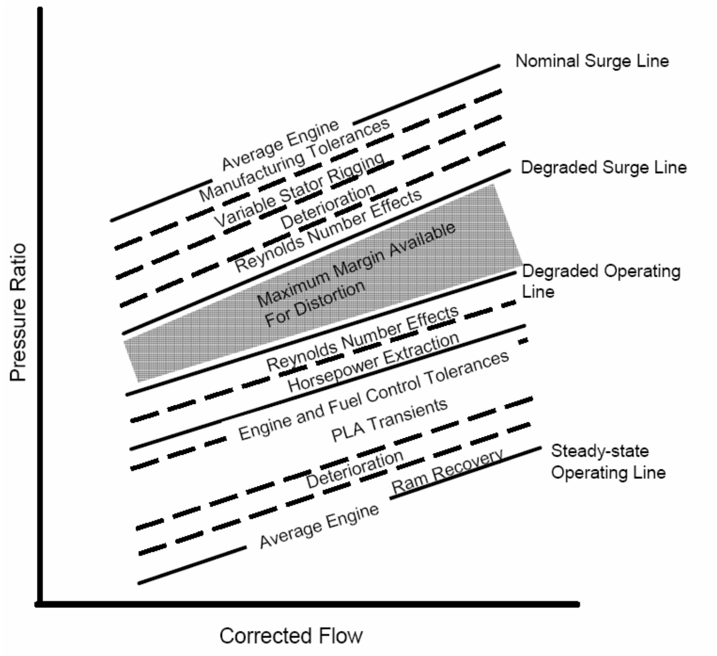

Figure 4: Factors affecting compressor stability margin[3].

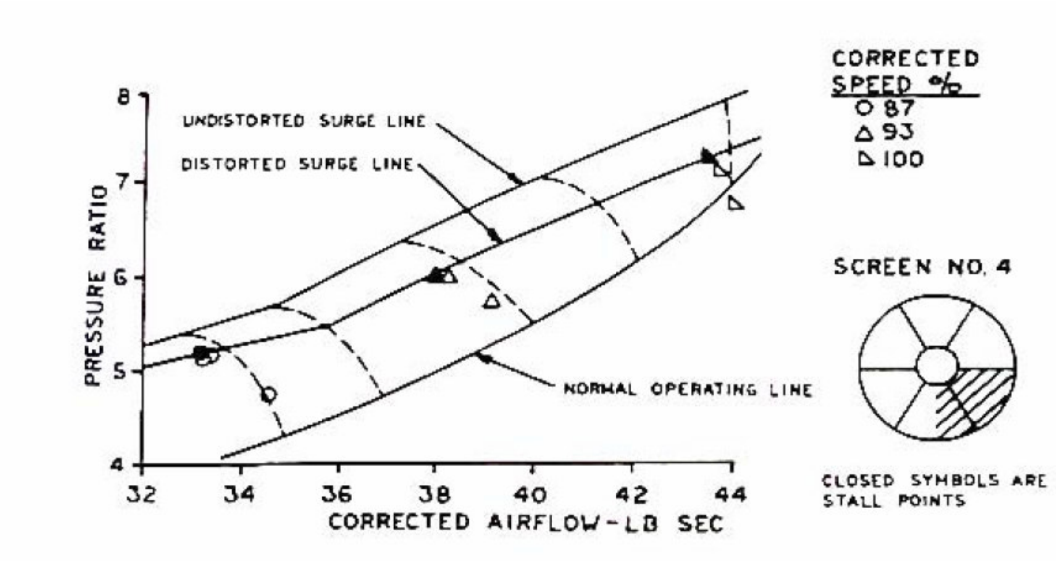

Figure 5: Distorted speed line for the circumferential distortion[2].

In figure 5, results are presented from engine testing showing the change in the operating point for the distorted flow compared to the 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[3]

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

We have identified in this paper the parameters that will affect air intake loss. These parameters are in the form of:

- 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
- Shockwave

Since the ***THRUST ARCHITECTURE*** contains only one single bend, these parameters are controllable through proper design consideration.

References

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

[2] Campbell, A. (1981). *An investigation of distortion indices for prediction of stalling behavior in aircraft gas turbine engines*. Master's Thesis, Virginia Tech.

[3] SAE S-16 Committee. (1983). *AIR 1419, inlet total-pressure-distortion considerations for gas-turbine engines.* Society of Automotive Engineers.

[4] ESDU (1975) Performance of circular annular ducts in incompressible flow. *Fluid Mechanics Internal Flow, 4*. London: ESDU.