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Aero-Engines Intake: A Review and Case Study

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Abstract

This paper presents an aerodynamic review for intakes of aero-engines. Classification of different types is introduced for both subsonic and supersonic aircrafts. Important parameters influencing intake performance like pressure recovery and spillage drag are discussed. In addition, crucial performance issues such as the angle of attack, ground vortex, swirl flow, noise propagation and icing are presented. These are critical issues which are carefully considered by airframe rather than engine manufacturers. Intake icing may be extremely dangerous and leads to drastic decrease in air mass flow and consequently aircraft propulsion.

Calculation of intake performance is explained. The effect of intake performance on the whole engine performance is highlighted. Numerical analyses for present and previous researches are explained and critical parameters are identified.

Finally, a case study resembling the intake of a high bypass ratio turbofan engine (in close similarity to that of GE CF-6 Turbofan Engine) is numerically analysed using the commercial code "ESI-CFD 2010" is thoroughly described and analysed. This paper is the first of a series of research work that will cover several R & D activities in HBPR and future EBPR turbofan intakes.

Keywords: Aircraft, Intake, Ground vortex, Swirl flow.

Introduction

Intake is the first module of aero-engines. Air mass flow rate through the engines influences both of the generated thrust/ power as well as its fuel consumption. Moreover, air mass flow rate depends on the efficiency of air intake. Such efficiency is achieved via a proper geometry design and accurate production.

Maintenance personnel during their Pre-departure checks (PDCs) check that the geometry of the intake coincides with the specs of manufacturers; its lips are free from ice/snow or any type of FOD.

Intakes of aero-engines used in airliners as well as military planes should provide the exact amount of air necessary for different flight conditions. Military aircrafts may have variable geometry intakes, while civil transporters have fixed geometry. Adjusting the flow pattern in this case, relies upon the rotational speed of the succeeding fan/compressors and variable geometry of the stators of one or couple stators.

Moreover, complexity of intake design arises from the flight of aircraft at different altitudes ranging from sea level to several ten thousand feet altitudes. Also, even it may take-off at negative ambient temperatures – Celsius- in cold areas up to fifties in hot area.

Military aircrafts meet worse flight conditions and shock waves are typical flow pattern for its intake.

Both the words intake and inlet are used alternatively. Intake is normally used in Britain while inlet is used in the United States. The word intake is a more accurate description of their function at low aircraft speeds, as mentioned by NASA Glenn Research Center [1]. Air intake duct is designed and manufactured by airframe manufacturer and not by the engine manufacturer. Both manufacturers cooperate in testing air intakes.

An aircraft will require one or more engines based on its mission and payload.

Intakes has to capture (collect) the proper air mass flow rate at each free stream Mach number. It sometimes changes its direction, and supplies this flow to the succeeding engine modules with as little distortion as is possible, to ensure smooth running and efficient propulsion. Moreover, the intake has to achieve all this with minimum disturbance to the external flow around the aircraft to generates the minimum external drag. In other words, for a successful operation of the engine along the desired flight envelope, the engine-intake compatibility is essential.

Noise level is an extremely critical issue for inlets. Thus all the present airliners use noise-absorbing or suppressing materials to cope with the international acoustics limitations [2].

All civil aircrafts (apart from small ones which are powered by internal combustion engines) as well as military ones are powered by gas turbine engines, which are also called jet engines. These are mostly turbofan engines and to a less extent turboprop engines. All gas turbine engines have an intake (inlet).

An air-intake is the component which fits an engine for a specific airframe of airliners. Air intake comes before the fan/compressor and it is located in the frontal portion of the fuselage as in fighter jets so as to permit efficient supply of air under various flight regimes. In the intake, air at free-stream Mach number is decelerated, thereby increasing the static pressure, and is then fed to the engine, [3].

Intake brings free stream air into the engine. Also, the intake sits upstream of the compressor and, while the inlet does not work on the flow, inlet performance has a strong influence on engine net thrust, [NASA Glenn Research Centre]. Intake feeds air at the compressor face at a Mach number in the range 0.3 to 0.5 with minimum turbulence [4].

The air intake of a fighter aircraft must meet the engine mass flow demand over a range of aircraft speeds and attitudes with high total pressure recovery and low distortion [5].

Air vehicle inlet design is a challenging task in that the designer should consider not only the constraints imposed by configuration features, like nose landing gears, weapon bays, equipment access panels, and forebody shaping, but also the quality of the air flow at the face of the engine during all phases of its flight envelope which means a wide range of speeds, altitudes, and manoeuvring conditions, [6].

There are mainly two important aspects of achieving airflow quality. First, the total pressure recovery should be as high as possible. Second, turbulence and distortion at the entrance of engine should be minimized [6].

Types of Intakes

Inlets come in a variety of shapes and sizes with the specifics usually dictated by the speed of the aircraft.

Subsonic Intakes

For aircraft that cannot go faster than the speed of sound, like large airliners, a simple, straight, short inlet works quite well. On a typical subsonic inlet, the surface of the inlet from outside to inside is a continuous smooth curve with some thickness from inside to outside. The most upstream portion of the inlet is called the highlight, or the inlet lip. A subsonic aircraft has an inlet with a relatively thick lip, Figure 1, mentioned by NASA Glenn Research Center [1].

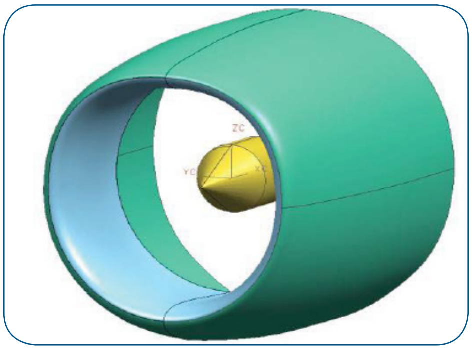

Figure 1: Subsonic Intake, CAD Model by Pierluissi et al [7]

Supersonic Intakes

An inlet for a supersonic aircraft, on the other hand, has a relatively sharp lip. The inlet lip is sharpened to minimize the performance losses from shock waves that occur during supersonic flight. For a supersonic aircraft, the inlet must slow the flow down to subsonic speeds before the air reaches the compressor. Some supersonic inlets, as in Figure 2, use a central cone to shock the flow down to subsonic speeds. Other inlets, as in Figure 3, use flat hinged plates to generate the compression shocks, with the resulting inlet geometry having a rectangular cross section. This variable geometry inlet is used on the F-14 and F-15 fighter aircraft. More exotic inlet shapes are used on some aircraft for a variety of reasons. The inlets of the Mach 3+ SR-71 aircraft are specially designed to allow cruising flight at high speed. The inlets of the SR-71 actually produce thrust during flight (NASA Glenn Research Center [1]).

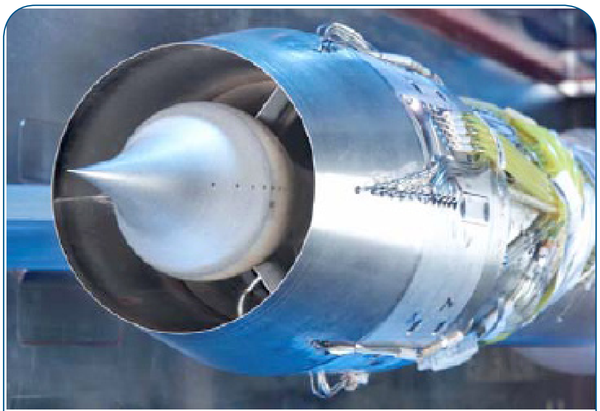

Figure 2: Supersonic Intake, by Loth and Babinsky [8]

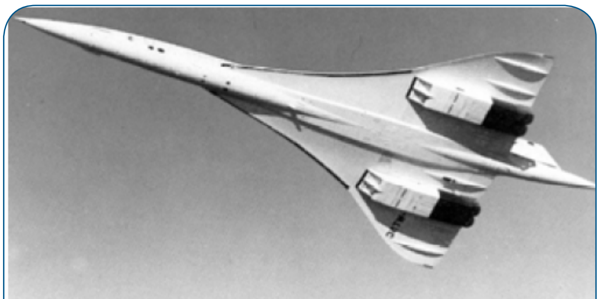

Figure 3: Rectangular-Supersonic Intakeof Concord Aircraft, by Loth and Babinsky [8]

Hypersonic Intakes

For ramjet-powered aircraft, the inlet must bring the high speed external flow down to subsonic conditions in the burner. High stagnation temperatures are present in this speed regime and variable geometry may not be an option for the inlet designer because of possible flow leaks through the hinges. For scramjet-powered aircraft, the heat environment is even worse because the flight Mach number is higher than that for a ramjet-powered aircraft. Scramjet inlets are highly integrated with the fuselage of the aircraft. On the X-43A, the inlet includes the entire lower surface of the aircraft forward of the cowl lip. Thick, hot boundary layers are usually present on the compression surfaces of hypersonic inlets. The flow exiting a scramjet inlet must remain supersonic, NASA Glenn Research Center, [1].

Intake Configurations

Twin Intake

Single engine high-speed aircrafts breathing system generally has twin intake ducts. It supplies air to the propulsion system through a multi-stage compressor. Twin intake ducts, also known as Y-shaped intake ducts, are used in various models of single engine fighter aircrafts, such as, LCA (Light Combat Aircraft), SM-36 STALMA (Short Take-off Advanced Light Multi-Role Attack), FC-1 (Fighter China-1) Xiaolong, Mirage 2000, J-7 (Jian-7), F-20 Tigershark, etc., [9].

Divided intake ducts are widely used for ingestion of atmospheric air to the single-engined fighter aircraft. These offer great flexibility to diffuse the incoming air over a short duct length and hence with a smaller pressure drop due to skin friction. The intakes are normally side-mounted and the two limbs of the duct merge inside the fuselage into one, Figure 4.

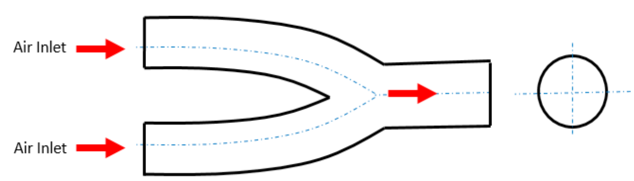

Figure 4: Sketch for Twin Intake, by present authors

Y-shaped ducts are a popular choice for air intakes in single-engine fighter aircraft. The intakes are normally side mounted and the two limbs of the duct merge inside the fuselage into one and feed the engine. Y-shaped ducts are normally expected to operate in a steady, symmetric manner. In this case, the engine mass flow demand is met by the two limbs by inducing equal mass flows, each being half of what the engine requires. Steady, asymmetric operation where the two limbs induce unequal mass flows, though not immediately obvious, can never be ruled out. The flow in this case, even if smooth in the individual ducts, can be expected to be highly distorted on mixing. The available duct length within the fuselages very likely to be insufficient to smooth out the distortion before the flow reaches the engine face. This Note proposes simple flow model that explains the phenomenon that causes transition from symmetric to asymmetric operation, [5].

Curved Intake

Many military aircraft engine intakes are strongly curved. Not only does the curved geometry cause sound to propagate differently from a straight intake, but also the in-homogeneity of the mean flow leads to refraction. For many military aircraft engine intakes, the curvature is significant and large, but varies on a length scale far longer than a typical sound wavelength. The diameter of the intake also varies slowly in this way, Figure 5, [2].

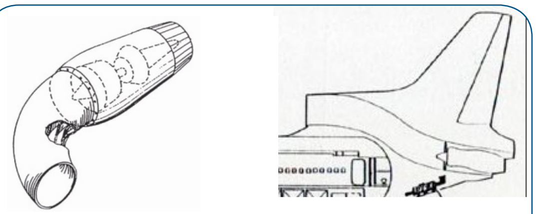

Figure 5: Curved Intake

Submerged Intake

A submerged (also known as flush mounted or tunnel) inlet is an attractive alternative design which can achieve lower drag and weight compared to conventional inlet, see Figures 6 and 7. Obviously, having small radar cross section makes this type of inlet more attractive from low observability and stealth technologies point of view. The objective was to examine a candidate submerged inlet for a generic subsonic vehicle by numerical simulation, [6].

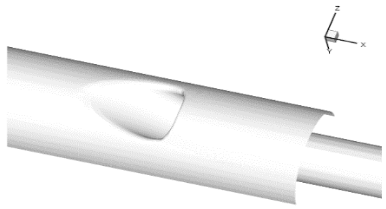

Figure 6: Submerged Intake, Taskinoglu and Knighty [6]

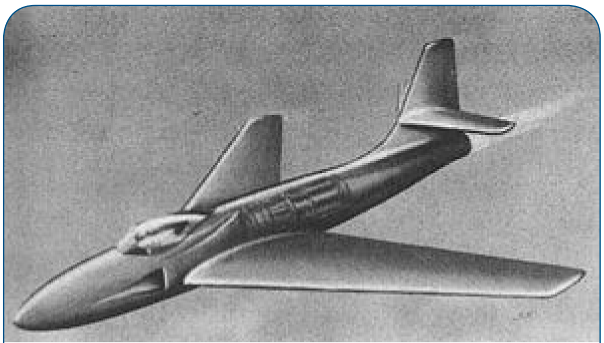

Figure 7: Submerged Intakes

Intake Performance

Flow Characteristics in Intake

From aerodynamics point of view, the flow in an intake is like the flow in a duct. The duct "captures" a certain stream tube of air, thus dividing the air stream into an internal flow and an external flow. The external flow preserves the good aerodynamics of the airframe, while the internal flow feeds the engine. The flow characteristics in podded intakes for four flow conditions are illustrated in Figure 8. In ground running (Figure 8-a), there will

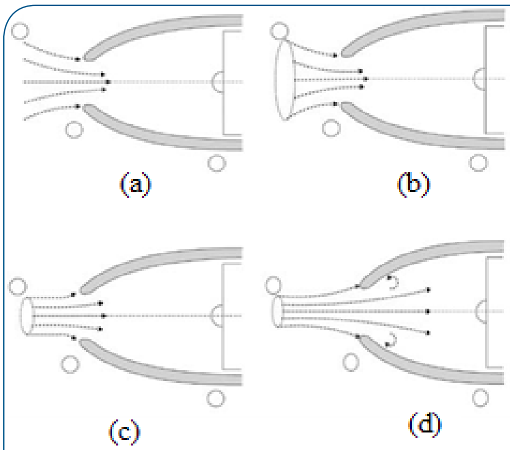

Figure 8: Flow characteristics of podded intakes: (a) ground run, (b) climb, (c) high-speed cruise, and (d) top speed, El-Sayed [10]

be no effective free stream velocity that results in a large induced flow capture area causing the streamlines to converge into the intake area. The ratio between the upstream capture area to the inletarea approaches infinity. The stream tube has a bell-shaped pattern. During climb, Figure 8-b, the free stream velocity will be lower than the intake velocity due to the requirement of high mass flow rates. This will also result in a larger entry stream tube area than the intake area (a convergent stream tube pattern). At high speed cruise (where $M = 0.85$, Figure 8-c), the entry stream tube will be smaller than the intake area and diffusion partially takes place outside the intake and partially inside and hence the air velocity attains lower values in the intake with a small resultant rise in pressure (15%).At top speed (higher than cruise where M = 0.95, Figure 8-d) the high pressure gradient on the intake lip can cause separation and an unstable flow into the intake.

Intake Efficiency

At high speeds, a good inlet will allow the aircraft to maneuver to high angles of attack and sideslip without disrupting flow to the compressor. Because the inlet is so important to overall aircraft operation, it is usually designed and tested by the airframe company, not the engine manufacturer. But because inlet operation is so important to engine performance, all engine manufacturers also employ inlet aerodynamicists. The amount of disruption of the flow is characterized by a numerical inlet distortion index. Different air-framers use different indices.

All intakes are based on ratios of the local variation of pressure to the average pressure at the compressor face. The ratio of the average total pressure at the compressor face to the free stream total pressure is called the total pressure recovery. Pressure recovery is another inlet performance index; the higher the value, the better the inlet. If the airflow demanded by the engine is much less than the airflow that can be captured by the inlet, then the difference in airflow is spilled around the inlet. The airflow mis-match can produce spillage drag on the aircraft, (NASA Glenn Research Center [1]).

The performance of the intake depends on various geometrical and dynamical parameters, namely, exit to inlet area ratio, shape of the inlet, angle of turn of the limbs, length of the duct, inlet Reynolds number, Mach number, inlet velocity ratio, and so on, [9].

Reference Points

Because the inlet does no thermodynamic work, the total temperature through the inlet is constant. Referring to the present research numbering as in Figure 8, free stream conditions are noted by a "0" subscript, the entrance to the inlet is station "1" and the exit of the inlet and entrance to the compressor is station "2". The inlet total temperature $\mathbf{T_t}$ ratio is $\mathbf{T_{t2}}$ divided by $\mathbf{T_{t0}}$ and is equal to 1.0.

$$\textbf{Inlet Total Temparature} = \frac{T_{t2}}{T_{t0}} = 1$$

Pressure Recovery

Referring to Figure 9, the total pressure $\mathbf{P_t}$ through the inlet changes, however, because of several flow effects. Aerodynamicists characterize the inlet's pressure performance by the inlet total pressure recovery, which measures the amount of the free stream flow conditions that are "recovered". The pressure recovery depends on a wide variety of factors, including the shape of the inlet, the speed of the aircraft, the airflow demands of the engine,

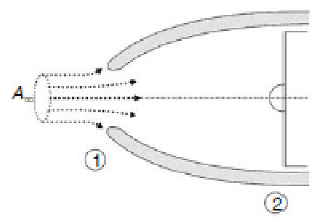

Figure 9: Reference Points of Subsonic intake, infinity symbol means O in the present paper, by El-sayed 2008, [24]

and aircraft manoeuvres. Recovery losses associated with the boundary layers on the inlet surface or flow separations in the duct are included in the inlet efficiency factor : η_i

$$\eta_i = \frac{P_{t2}}{P_{t1}} = 1$$

In case of subsonic flight speeds, no another losses is found. For Mach number M less than 1, the Military Specifications value of recovery is the inlet efficiency.

At supersonic flight speeds, there are additional losses created by the shock waves necessary to reduce the flow speed to subsonic conditions for the compressor.

The (Mil. Spec.) loss is estimated by inlet recovery. The magnitude of the recovery loss depends on the specific design of the inlet and is normally determined by wind tunnel testing.

- For M>1 : $IPR = \frac{P_{t2}}{P_{t0}} = \eta_i \times 1 \ -0.075 \times [M - 1]^{1.35}$
- For M < 1 : $IPR = \frac{P_{t2}}{P_{t0}} = \eta_i \times 1$

For hypersonic inlets the value of pressure recovery is very low and nearly constant because of shock losses, so hypersonic inlets are normally characterized by their kinetic energy efficiency, (NASA Glenn Research Center [1]).

Total pressure recovery (which is the ratio of total pressure at the exit to that at the entry) in subsonic intakes is generally very close to unity and depends primarily on the location of the engine relative to the airframe. For example, the intake of an engine located on the wing (like the Boeing 777) would have a relatively obstruction-free flow leading to high pressure recovery, while, that for an engine located at the vertical tail (e.g. Boeing 727) would not be able to perform as well [3].

Spillage Drag

There is an additional propulsion performance penalty charged against the inlet called spillage drag. Spillage drag, as the name implies, occurs when an inlet "spills" air around the outside instead of conducting the air to the compressor face. The amount of air that goes through the inlet is set by the engine and changes with altitude and throttle setting. 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. 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. Inlet aerodynamicists account for this effect with a correction factor K that multiplies the theoretical spillage drag. Typical values of K range from 0.4 to 0.7. But for a given inlet the value is determined experimentally. The form of the theoretical spillage drag D spill is very similar to the thrust equation:

$$D_{spill} = K(m_1[V_1 - V_0] + A_1[P_1 - P_1])$$

Air intake spillage drag is not a drag in the traditional sense, but a by-product of the thrust and drag definitions that are necessary for correct engine/airframe force accounting. Spillage drag takes the form of a correction applied to the vehicle as a result of the influence of the propulsion system. It is defined as the change in vehicle drag due to the variation of intake mass flow from a datum value and is effectively a correction to compensate for the fact that the air entering the intake is not at free stream conditions. Spillage drag is composed of two components, the additive or pre-entry drag and the cowl thrust. The additive drag is the force acting on the stream tube ahead of the intake and the cowl thrust is a force of opposing sign, which at some conditions may cancel the pre-entry drag. For a fixed geometry supersonic intake operating at subsonic conditions the un-recovered pre-entry drag may be as much as ten percent of the total aircraft drag, [11].

As air is brought from free stream to the compressor face, the flow may be distorted by the inlet. At the compressor face, one portion of the flow may have a higher velocity or higher pressure than another portion. The flow may be swirling or some section of the boundary layer may be thicker than another section because of the inlet shape. The rotor blades of the compressor move in circles around the central shaft. As the blades encounter distorted inlet flow, the flow conditions around the blade change very quickly. The changing flow conditions can cause flow separation in the compressor, a compressor stall, and can cause structural problems for the compressor blades. A good inlet must produce high pressure recovery, low spillage drag, and low distortion.

Because an inlet is essentially a hollow tube, the weight considerations of the inlet are small compared to the compressor or turbine. For ramjet and scramjet inlets, the materials used in the inlet must withstand high temperatures.

Problems Related to Subsonic Intake

Angle of Attack

The flow instabilities in the intake duct during the landing condition for different angles of attack for the aircraft have been analyzed in the computational investigation. Incompressible steady-state flow simulations have been carried out at various angles of attack, ranging from 0° to 30°, for the forebody-intake duct assembly using a commercial CFD code, FLUENT, [9].

There is no degradation in pressure recovery to 30-deg angle of attack and stable operation to 40-deg subsonically, with an increase in pressure recovery with the angle of attack at supersonic speeds, [12].

Ground Vortex

A jet engine running near the ground generates a low pressure zone near the intake which in turn gives rise to ground vortices, Figure 10.

These vortices may in turn be strong enough to lift small pieces of concrete or small particles from the ground leading to maintenance problems. The ground vortices are far from being stationary, making their prediction rather difficult. The presence of an air-intake vortex system, near the ground can be observed on the runway during the taxi phase or during the take off if tracer particles are present (snowflakes or rain droplets). A group of researchers from MIT [13] discussed a mechanism of formation of these vortices. Ground vortices can, however, be formed also in the absence of any ambient flow [14-17]. Yet, in both cases the flow generated by the sucked air is similar, which has been confirmed experimentally (De Siervi et al., [18]) and computationally.

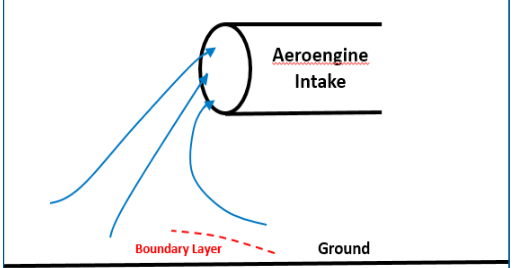

Figure 10: Ground Vortex Formation

Shin et al. [19] studied computationally the comparison between four turbofan engines in the ground vortex effect. They studied the full-scale geometry. These four engines are: CF6-80a, Trent-700, Trent-900, and GE-Nx-1b64. They found that there are two main types of vortices around intake which are: an inlet vortex, and a trailing vortex, Figure 11.

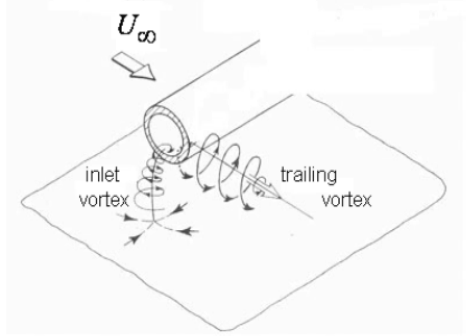

Figure 11: Sense of rotation of the inlet vortex and the trailing vortex

Swirl Flow

In modern combat aircraft, the S-type intake is very commonly used. However, the swirl flow which is always accompanied by an S-type intake may cause serious engine/intake compatibility problems, such as engine surge and fan vibration. Aulehla [20] found that the swirl in S-type intake may be classified into two components:

(1) Twin swirl or vortices due to the internal S-duct profile;

(2) Bulk swirl which is independent of the bend (in the S-duct) itself.

The twin swirl is the more stable component and less easily attenuated. In contrast, the bulk swirl is rather sensitive, and changes considerably with the flow conditions. For the starboard intake of the twin side-by-side intake system, the bulk swirl rotates in a direction opposite to that in which the engine rotates, which can cause engine surges, while the port engine is surge-free at the same operating conditions, as the bulk swirl rotates in the same direction as does the engine. That is the essential requirement for the early intake/engine incompatibility of a Tornado which is called the "handed" effect. For this reason, the swirling effect is at least of equal importance for intake aerodynamics, as total pressure recovery, flow distortion, and spillage drag, [21].

Noise Propagation

Francescantonio [22] computed fan noise transmission through and radiation from realistic lined intakes via the GFD (Green's Function Discretization) method. The high accuracy of this wave-based discretization method and the use of an" exact" radiation condition supplied by an integral formulation enable genuine 3D simulations at fan-radius Helmholtz numbers up to 22, within practical times on single processor platforms. Helmholtz numbers of 50 can be achieved on a 10-CPUs parallel platform within equivalent computational times. Both axisymmetric and negatively scarfed configurations are considered. For the scarfed case, the effect of axial and circumferential segmentations of the acoustic treatment on the sound radiation is explored at a given frequency and spinning mode order. It is shown that the presence of rigid splices reduces the attenuation effect of the acoustic treatment. Furthermore, the effect of the scarf angle on the upward/downward peak-levels observed for a rigid-wall configuration is no more evident when a segmented liner is considered.

Achunche et al, [23] presented a prediction method for fan tone noise propagation and radiation in intake. The results from the predictions are validated against rig measurements. In the prediction method for fan tone noise propagation and radiation, the source can be described as multimodal at subsonic tip speeds, and composed of a multimodal content and a high pressure amplitude rotor-locked content at supersonic tip speeds. In-duct sound pressure level (SPL) measurements from mode detection have been used to calibrate the predictions.

Efraimsson et al, [24] simulated the propagation of acoustic waves in the air intake of a turbo-fan engine using a commercial Navier-Stokes solver. Three different acoustic modes were studied. From the results, it can be concluded that the propagation of sound waves in a curved intake can indeed be simulated using a commercial CFD solver. Also, the acoustic source, when given as a boundary condition, should be set at the fan plane. A strong influence of the flow or the curved geometry is identified, yielding a focusing of sound waves to the middle part of the duct. A transmission loss of the acoustic power from the fan plane to the inlet plane of around 5 dB is identified for the first radial modes for acoustic powers in the interval [128 dB, 158 dB]. Non-linear effects are identified for powers of 148 dB and higher, which seems reasonable. Finally, a shielding effect of supersonic regions is identified.

Intake Icing

Test results show that icing can reduce wing lift by up to 30% and increases drag by up to 40%. Many icing-related mishaps take place when ground de-icing was not administered properly or at all. However, icing build-up can happen quickly and catch you with your guard down.

Icing can do serious damage to fixed wing as well as rotary wing aircraft, but it has a different effect on each. Ice on rotor blades and propellers can cause catastrophic vibrations. It accumulates on exterior moving surfaces, it can affect the control of the aircraft. It can make wings, blades, ailerons, rudders and elevator sharder to move, requiring more power.

Ice can break away from an aircraft's exterior surface and be ingested into an engine intake, which causes FOD. Operation of control surfaces, brakes, and landing gear can be lost. Ice can seriously obstruct the vision outside; it can give false instrument readouts.

There are two main types of icing - structural icing and induction icing and each has its own subcategories. Structural icing is primarily the icing that sits on a surface, such as an aircraft windshield, fuselage or engines. Three basic types of structural icing exist, one of which is clear ice. Clear ice is the most serious form of icing since it sticks so firmly to the aircraft. It is heavy and harder to get rid of than other forms of ice.

Rime ice is more dense, milky and granular in texture. It has a rougher surface than clear ice does, and it is very brittle due to its higher air content. This brittleness makes it easier to remove from the aircraft's surfaces.

In Fayed, [25] study, the effect of ice accretion (due to super-cooled water droplets in the clouds) on the performance of the intake of a high bypass ratio turbofan engine considering (GE-CF6), as a typical example, was investigated. The ice accretion on the intake installed on CF-6 turbofan engine when passing through clouds, was modelled to investigate its effect on the performance of the engine.

Numerical Analysis of Intakes

Behrouzi and McGruik [26] predicted numerically the flow field associated with a generic twin-jet plus intake model operating under ingestion flow conditions. The results have been compared with laser Doppler anemometry (LDA) validation measurements taken in a specially designed test case configuration. The (k-ϵ) turbulence model and both first-order and second-order (QUICK) convection discretization schemes were employed. Fine meshes and second-order accurate discretization were found essential to produce solutions close to grid independence. A reasonable prediction of the general flow pattern has been achieved. Several features of the mean velocity field were close to the experimental results. However, the k-ϵ model was shown to produce significant errors in the prediction of the forward penetration distance of the ground sheet flow and in the shape of velocity profiles and turbulence levels near to the intake. Figure 12 shows some of their results. The CFD prediction of the flow field associated with a generic twin impinging jet plume/intake model was carried out and compared with available LDA experimental data. With the mesh density of a quarter of a million cells adopted, the use of second-order convection differencing was found sufficient to produce solutions close to grid independency. Prediction of the turbulent fluctuations, especially near the intake and in the ground vortex forward penetration regions, was unsatisfactory.

For steady state time-averaged predictions, the k-є model was shown to produce errors in the prediction of the forward penetration distance of the ground flow and in the shape of velocity profiles and turbulence levels near to the intake.

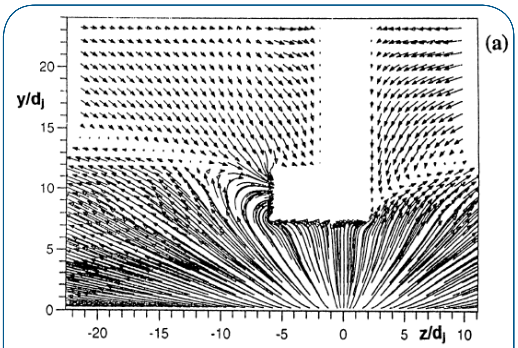

Figure 12: Streak-line pictures in the fountain plane (x/dj= 0) for a combined twin-jet/intake system with no cross-flow, Behrouzi and McGruik [26]

Case Study

In the current work, the authors used commercial code, ESI-CFD 2010, to show flow distribution at intake of GE CF-6 Turbofan Engine (as a case study). 3D numerical model is introduced to simulate flow in the engine at M=0.85 of the aircraft and at altitude 10,680 m. The computational domain uses about 500,000 nodes.

Figure13, Figure14, and Figure 15 illustrate the contours of Mach number, static-to-to-total temperature ratio, static-to-total pressure ratio, respectively. Figure 16 shows the streamlines at different aircraft velocities.

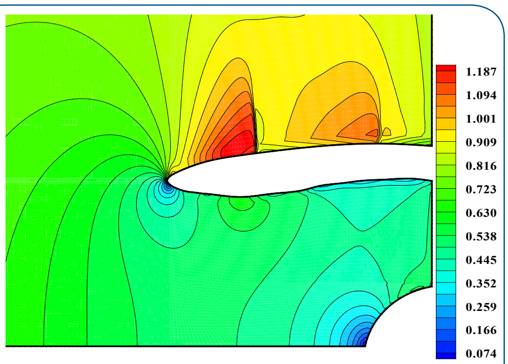

Figure 13: Mach number contours at M =0.85and latitude 10,680 m

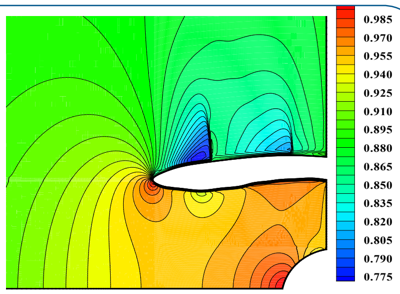

Figure 14: Static to total temperature ratio contours at M =0.85 and latitude 10,680 m

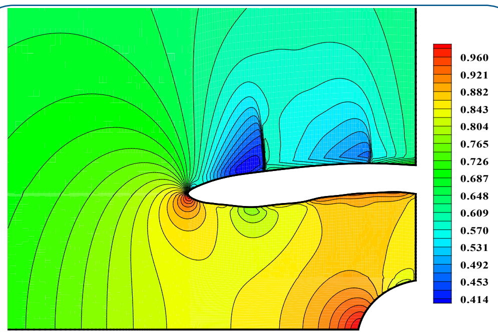

Figure 15: Static to total pressure ratio contours at M =0.85and latitude 10,680 m

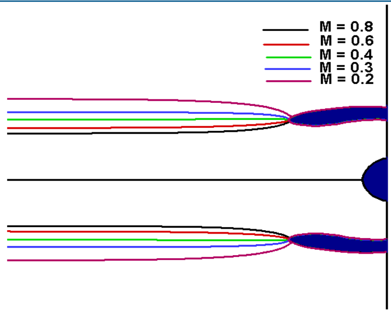

Figure 16: stream lines for different flight Mach number and latitude 10680 m

Conclusion

This paper has provided guidelines to research in the intake of aircraft engines. It also can be helpful for other researches through providing new design trends. The present review also points towards special topics like: acoustics, icing, swirl-flow, ground-vortex, cross-flow, and spillage-drag.

From the present case study, there are main points are concluded such as:

1- The commercial code "ESI-CFD 2010" is valid for simulation 3D air-flow in aero-engine intake.

2- (k-e) turbulence model is better than other turbulence models for simulating air-flow in aero-engine intake.

3- Turbulence (k-e) model is employed in predicting air-flow in the intake of HBPR turbofan engines.

4- Using sector domain with 45-degree angle is justified for simulating 3D flow within the turbofan intake.

Forthcoming research topics will be:

1- Modifying the intake design to improve its performance with ground vortex and cross flow.

2- Study of the effect of intake performance on the whole engine performance and efficiency.

3- Simulate the swirl flow, cross-flow, and ground vortex in intake with different engine installation. Then, the best engine installation to get high performance is determined.

Abbreviations

CFD : Computational Fluid Dynamics

D_{spill} : Spillage Drag

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FOD : Foreign Object Damage

K : Lip suction factor

V : Velocity

A : Area

η_i : Inlet efficiency

M : Mach Number

P_t : Total Presure

IPR : Internet Presure Recovery

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