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Advances of the Aerodynamic Aspects of Serpentine Air-Intakes: A Review

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Abstract—*As aircrafts continue to evolve, the requirements for their development are becoming more and more precise. The thrust to weight ratio requirement is increasing, which require either lighter aircrafts, or more powerful engines which tend to add weight. The technology required to meet the challenge is the highly integrated propulsion system incorporating a compact serpentine air intake. Highly compact serpentine inlet ducts provide advantages over traditional ducts in many ways. By shortening the inlet, the overall aircraft length can be reduced. A short length saves material, reducing weight and cost which results in a compact aircraft and improves engine performance. The main purpose of Serpentine duct diffuser in aircraft propulsion systems is to supply the ambient air from the wing or fuselage mounted intake to the engine compressor (i. e. , aerodynamic intake plane – AIP) for thrust generation. To achieve suitable performance, the Serpentine duct must also incur minimal total pressure losses and deliver nearly uniform flow with very small or no cross-flow velocity components at the AIP. A compact Serpentine duct is characterized by its extreme wall curvature. The review paper is aimed to understand the previous works carried out to analyze the flow characteristic and the flow control strategies used. The advantages of serpentine duct includes better flow uniformity that too in a short length, but at the cost of secondary flow generation, flow distortion, pressure losses and turbulence related characteristics.*

1. INTRODUCTION

Development of aircrafts has become more advanced, and thus the designs are becoming more compact and complex to make these survivable, affordable, comfortable following low drag constraints.

Distorted flow at the engine face or the AIP drives aeromechanical stability, operability and acoustic problems within the fan and compression system. The distortions arise due to flow separations at the cowl lip, low momentum boundary layer flow, internal flow separation, and diffuser effects of the duct such as secondary or cross flows [6]. A compact Serpentine duct is characterized by its extreme wall curvature. The advantages of serpentine duct includes better flow uniformity that too in a short length, but at the cost of secondary flow generation, flow distortion, pressure losses and turbulence related characteristics.

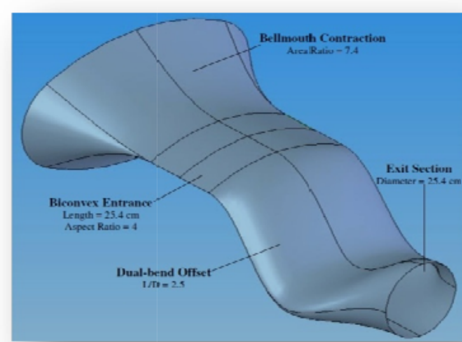

Fig. 1: Serpentine Inlet Model [9].

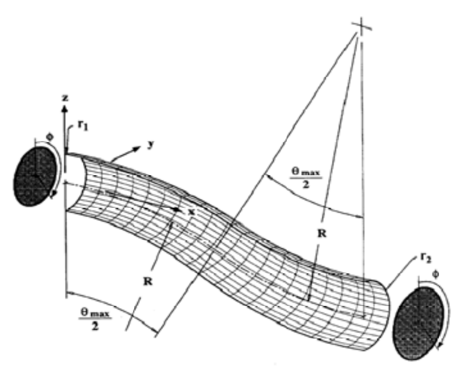

Fig. 2: Diffusing Serpentine Duct Geometry [14]

The secondary flow generated within the serpentine duct is more severe at off-design conditions [11]. The effect of off-design conditions (angle of attack and asymmetric distortion) is not yet well understood for these ducts, design revisions are required in order to ensure acceptable flow quality at any condition that may occur during a flight mission. Serpentine inlet ducts are utilized in many aircraft where the inlet capture area is located off the thrust line or to conceal the engine compressor face. These ducts can guide the uniform free stream through the ducts and deliver it with the most effective and suitable velocity distribution to the engine face while converting kinetic energy to static pressure. These serpentine shaped ducts do not provide a direct line of sight to the compressor blades, thus hiding the engine from incoming radar waves.

2. DEVELOPMENT OF SERPENTINE AIR INTAKES

The Serpentine air-Intakes provide a useful technology to manufacture 5th generation aircrafts having stealth technology. Serpentine inlet duct has been widely used for military and commercial aircraft. Inlet should decelerate the flow to the desired velocity while maintaining high total pressure recovery and flow uniformity. Serpentine ducts have some ratio of diffusion from inlet area to exit area, causing flow to decelerate. This diffusion is useful for serpentine inlets because the diffused flow has a higher pressure and matches the engine inlet flow velocity requirements, improving the performance of the jet engine. But in Serpentine inlet duct two bends give rise to streamline curvature. Inlets with short lengths and curvature are required for applications. Such short inlets are responsible for cross-stream pressure gradients which cause secondary flows and separation. The overall result is a loss of total pressure as well as distortion at the AIP, where the exit of inlet duct meets the compressor; diminishing the system performance. Therefore, flow control technologies based on passive and active techniques are applied to minimize the pressure loss, distortion and unsteadiness, and improve the system performance. The inlet aerodynamics gets more complex due to thick boundary layer near separation approaching the inlet, shocks at transonic speeds, and adverse pressure gradients at inlet blockage.

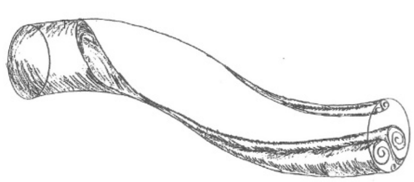

Fig. 3: Natural Vortices in Serpentine inlet [17]

The Serpentine duct was intentionally designed to incorporate as many of the complex three dimensional flows, including the possibility of unsteady streamwise separation, associated with geometry. Due to the curvature, flow distortion and total pressure loss at the engine face arise, leading to reduction in propulsion system performance. Secondary or cross flows are common within serpentine inlets as a result of centerline offsetand flow turning. Altering the cross-section of the duct generates large streamline curvature creating adverse pressure gradients along the surface of the duct, leading to significant secondary flows. These secondary flows form rotating vortices at the exit of the duct and are responsible for much of the distortion at the inlet AIP. Inlet designers need to reduce the size of the separation and distortion, whileengine designers must design engines capable of withstanding the distortions and pressure losses created.

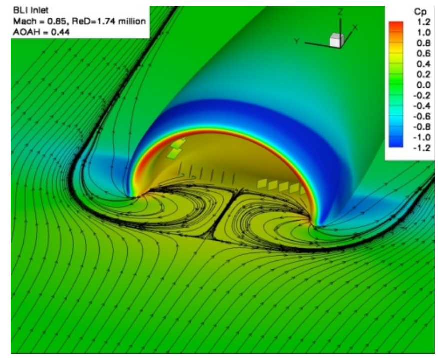

Fig. 4: Vortex Formation at the Inlet Lip/ Airframe Interface [6]

3. FLOW FIELD IN A SERPENTINE DUCT

Several parameters have been introduced about the air intakes.

- **Aerodynamic Interface Plane:** Experimentally, it is almost difficult to measure flow parameters at a compressor face when the engine is running. AIP is a plane forward of the compressor face but sufficiently close to the compressor face to have a very similar flow field".
- **Total Pressure Recovery:** In general, any duct has its specific friction and loss. The pressure loss is defined as the ratio of pressure difference through the duct to the dynamic pressure.
  Pressure loss$=\Delta p/q$
  $= (p_i-p_f)/q$

Where, p_f is the mean total pressure at AIP, p_i is the total pressure at inlet and q is the dynamic pressure. Then the **total pressure recovery** can be expressed as:

= 1- pressure loss
$= 1- \Delta p/q$
$= 1- (p_i-p_f)/q$

- **Total Pressure Distortion:** One of the main tasks of the air inlet is to deliver air uniformly to the compressor blades. This uniformity consists of total pressure, static pressure, total temperature, or a combination of these. If one of these parameters becomes non-uniform, distortion is said to be occurred. Furthermore, if the flow passing the duct has an angle with the engine longitudinal axis, another distortion called swirl occurs.

There are mainly two types of total pressure distortion:

1. **Steady distortion**. Steady distortion is defined as any non-uniformity of total pressure distribution in any section of the air intake. There is always a radial non-uniformity of pressure in sections of the duct because there is a boundary layer on the walls due to the viscosity of the air even in the absence of flow separation. It is common to neglect radial distortion in computations but to consider circumferential distortion because the aerodynamic loading on the compressor blades is on the circumferential direction.
2. **Dynamic distortion**. If the total pressure distortion at AIP changes with time or if is of a kind of spatially non-uniform, it is called dynamic distortion.

Two bends of the Serpentine inlet give rise to streamline curvature. Also increasing cross-sectional area can lead to adverse pressure gradients. The curvature due to offset can lead to two separationregions, worsened by the amount of offset. Generally, separation occurs at the first turnof the Serpentine duct on the bottom face. This is a result of an attempt of low-momentum flow to accelerate over the curved wall surface. The top surface of the second bend often leads to a separated region as well. This separation can be smaller than the first, and difficult to detect.

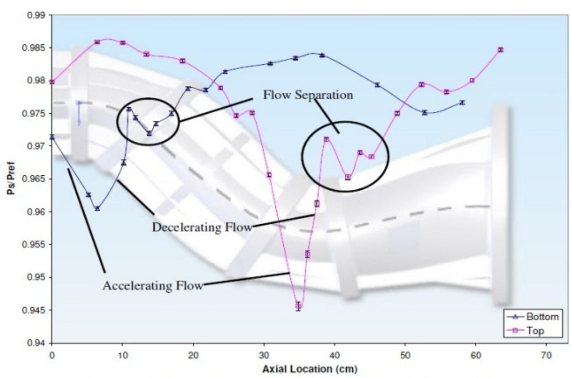

Fig. 5: Wall Static Pressure Distribution [9]

As the flow decelerates it experiences a significant adverse pressure gradient that stagnate the low-momentum boundary layer flow, forming a blockage and separation “bubble”. Secondary or cross flows then become common within serpentine inlets as a result of centerline offset and flow turning. These rotational flows are a major cause of pressure loss and distortion at the engine face, circumferential distortion in particular.

Duct turning produces swirl because the centrifugal forces set up a transverse pressure distribution moving the low energy duct wall boundary layer fluid towards the convex side of the curve and the high energy core flow towards the concave side [6]. In general, inlet swirl patterns form as a superposition of bulk and twin swirl. Bulk, or mean, swirl is produced when a region of low energy (total pressure) is located in one position of the duct perimeter. This low energy region is typically due to a separation, and is very sensitive to flight condition and inlet installation. The circumferential location and severity of these flow separations is affected bythe flight condition and installation, which may or may not exist for all operating conditions. Twin swirl is produced in all curved ducts as a result of centrifugal forces pushing the high energy core flow towards the outside of the curve. The high energy flow forces the wall boundary layer flow around the perimeter to move inward. The first bend in the Serpentine duct creates a top to bottom pressure differential that forces flow along the duct wall. These transverse velocities result in the formation of a pair of counter-rotating vortices.

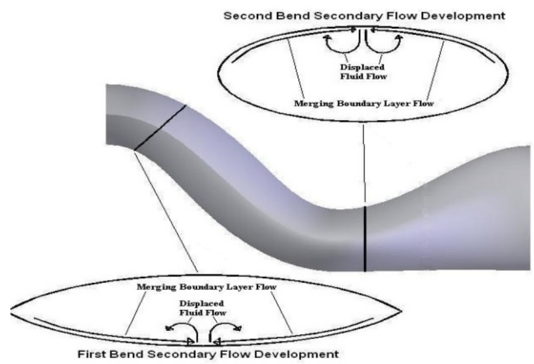

Fig. 6: Secondary Flow Development at the Bends of a Serpentine Duct [9]

BLI has additional effects in the formation of vortices. Secondary flows tend to move duct wall boundary layer towards the low pressure side (bottom of the first bend). Boundary layer’s slower velocity produces smaller centrifugal force than high energy core flow. The balance of the forces migrates along the wall towards the inside of the bend more readily than the core flow. Twin swirl vortices collect the boundary layer into a pocket located at the bottom of the duct and bottom center of the AIP [6]. Forcing the ingested boundary layer places low energy flow in the region of high wall turning, increasing the tendency of separation. The secondary flow [9] in these duct geometries conduct significant secondary flow structures, leading to large amounts of pressure loss and flow distortion. Poor pressure recovery results in reduction in overall engine performance and decreased fuel efficiency, while engine face plane distortions causing instabilities in the compressor dynamics, lowering engine surge and stall limits. The circumferential distortion pattern acts as an unsteady forcing function, inducing blade vibration that can result in structural fatigue and failure. This occurs when the rotor blades pass through regions of reduced axial velocity (i. e. , where the total pressure is low). In these locations, since the flow velocity component due to rotation becomes greater with respect to the axial component, the blade incidence angle is increased. Much like the stalling of an airfoil at high angles of attack, the flow over the blade separates at these large incidence angles. This action changes the loading on the blade and creates flow instabilities that convect through the later compressor stages.

Many investigations have explained the development of the secondary flow in serpentine ducts, characterized by a pair of large, counter-rotating vortices. Centrifugal forces [9] have considerable effect over the sharp curvatures of serpentine duct. When negotiating a bend, a centrifugal force is generated on the core flow, causing it to accelerate. This action, in addition to flow separation towards the inner region of the bend, produces a pressure differential, by which the pressure at the inside of the bend is lower than that at the outside of the bend. The consequence of this cross-stream pressure inconsistency is migration of the boundary layer flow towards the center of the duct, where the merging flow is pushed away from the wall and back towards the outside of the bend. From this motion, the lift-off of two counter-rotating vortices is produced.

The compact nature of the duct limits the length for diffusion and dissipation of the secondary flows and leads to greater distortion levels at the engine fan face. This inlet distortion can produce a reduction in stability margin for the compressor or fan of the turbine engine plus it can result in high cycle fatigue, leading to catastrophic loss of aircraft, loss of operability, and increased maintenance costs. The area ratio and transitioning cross-sections can also contribute to the inception of flow separation. The flow in the center of the duct has a higher velocity and will be subjected to a larger centripetal force than the flow near the wall at the inside of the turn which has a lower velocity. The low velocity near the wall is due to the no slip condition where the fluid velocity goes to zero at a stationary wall. This variation in centripetal force leads to secondary flow which circulates from the center region towards the wall and from the wall into the center region. The flow separation at the first turn is believed to be due to the low momentum, large boundary layer fluid from the first turn in combination with a large increase in cross-sectional area (high diffusion rate).

The studies on some particular geometry show one set of counter-rotating vortices from the first turn of the Serpentine duct while the second turn does not always produce additional vortices. The formation of vortices is dependent on the radius of curvature of the turns, the angle of the turns, the rate and degree of change in cross-sectional area, and the change in cross sectional shape. Embedded engine systems require boundary layer ingesting serpentine inlets to provide the needed airflow to the engine. These inlets produce distorted flow profiles. Proper design of these requires understanding of the underlying fluid dynamics that occur within serpentine inlets. Shape effects and static pressure distributions determine flow transport within the inlet.

4. FLOW CONTROL STRATEGIES ADOPTED FOR SERPENTINE AIR-INTAKES

The complexity of modern aircraft enforces strong geometric constraints to the air inlets. A significant drawback of serpentine geometry is the appearance of a separated boundary layer located in the curve, which causes decrease of the total pressure of the gas entering the compressor. Moreover, the strong curve is responsible for the development of a secondary flow composing of counter rotating vortices and flow distortions. Both the aspects degrade the performance of a propulsive system. Thus, it is highly desirable to avoid boundary layer separation. The improvement in flow quality is important because the uncontrolled flow exiting a serpentine inlet duct poses challenges for the gas turbine engine following the inlet duct. The stability margin of the engine can be affected by the flow non-uniformity. Instead of controlling the size of serpentine ducts, incorporating flow control techniques in these has received a great deal of interest. The major separation control strategies are [10]:

- 1. Tangential blowing to directly energize the low momentum region near the wall;
- 2. Wall suction to remove the low-momentum region;
- 3. Vortex generators (VGs) in the form of vanes and bumps; and
- 4. Forced excitation devices.

The concept of vorticity signature is used in designing the vortex generating jets. Vorticity signature is a principle that states that the strength, distribution, and secondary flow field interaction of the vortices generated by flow control devices are the primary means by which secondary flow control is achieved. Tangential blowing and suction are very effective in controlling separation. However, these strategies require a high mass flux source, thus they are rarely used. VGs are one of the methods most investigated. Numerous configurations, shapes and sizes have been explored to control boundary layer separation. The mechanism for reattachment as suggested by these studies is that VGs produce strong vortices, which enhances the mixing between the high-momentum core flow and the low-momentum boundary-layer flow, thus energizing the boundary layer fluid. However, VGs are a passive control strategy which is somewhat limited; they are fixed and can be optimized (location, size, and other parameters) for specific operating conditions.

Unsteady flow control techniques have received more attention recently and have been shown to be quite effective in controlling separation. Among these methods, synthetics microjets have shown some benefits. Synthetic jet actuators were placed within a region of a separated flow in a diffuser, leading to flow reattachment. Active flow control using array of fluidic actuators based on synthetic jet technology has already been applied to internal flows in diffusers [15]. It is noteworthy that jets can lead to flow reattachment even though they are placed downstream the separation of point. One important characteristic of the flow is the large pressure loss that occurred on the top surface of the inlet at the second axial location. This location would be the good choice for inserting some type of active flow control to help reduce the pressure losses [7]. Zero-Net-Mass-Flow (ZNMF) jets are created from the working fluid of the flow in which they are deployed. Linear momentum is transferred from the actuator to the fluid without net mass injection. Thus, in these types of actuators no additional mass flow is required. The ZNMF jets are produced by an oscillating pressure in a cavity which creates a phase of blowing and a phase of suction through the sharp edges orifice of the cavity. In the case of a round jet, the ZNMF jets are formed of vortex rings during the phase of blowing. These rings move sufficiently far from the orifice by their self-induced velocity during the blowing phase to be mostly unaffected by the following suction phase. During the suction phase, ambient fluid is entrained into the cavity.

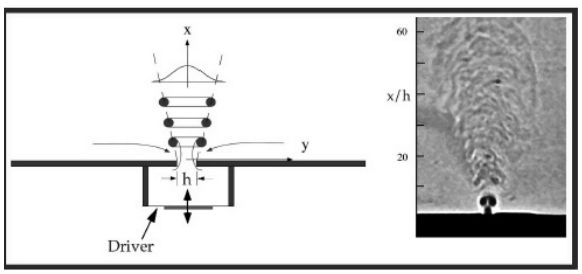

Fig. 10: Schematic of ZNMF jet formation [18].

Computational analysis has shown that flow control implementing micro-fluidic vortex generators significantly reduces the losses. Besides improvement in average total pressure recovery across the engine face and reduction of local pressure loss, it is observed that as the aircraft's airspeed increases, the flow control system becomes more effective.

5. SUMMARY

Angela C. Rabe[11] in her experimental results showed large total pressure distortions without flow control. With the addition of flow control, the increased pressure loss in the side regions is unaffected, but the large pressure loss at the top of AIP is improved. Circumferential distortion is lower for off-design conditions due to more uniform total pressure loss. The pressure recovery is lower for off-design conditions than for design or cruise conditions. The radial distortion decreases for off-design flight conditions due to increased flow uniformity while the cruise condition yields an increase in radial distortion. The increase is due to total pressure losses in the tip region. Nima et al. [8] found out that greatest amount of total pressure distortion is seen at positive stall condition. The uniformity of flow entering the duct influences the total pressure distortion; entering of turbulent boundary layer to the duct and the angle of attack eliminates the desired effect of low speed in positive stall condition. Turner[5] concluded in his experiment that without the flow control the distortion characterized by low pressure regions in the engine inlet face were enlarged during dynamic runs while with the flow control the total pressure recovery across the whole face was improved by 4% and maximum pressure loss was reduced by 10%. Dragan[12] reported that because of curved shape, inherent to serpentine surfaces, air is accelerated under Coanda effect and in some cases reaches supersonic speeds which results in shock waves.

6. FUTURE WORK

1. The effect of total pressure loss in the tip region (Angela Rabe[11]) on the compression system is yet to be understood properly and remains a potential area to be studied.
2. An active sensing technique can be developed for the application of closed loop control system.
3. Knowledge of complete velocity and pressure field is required to investigate effects on engine performance. Therefore, experiments measuring these across AIP are necessary.
4. The testing for high velocity jets is an important area where literature is less.
5. The study with the use of variable stator in front of compressible rotor can be done to study the improvement in engine efficiency and engine airflow.
6. The flow control strategies and the effective positions for these to be placed is yet a topic of discussion.
7. The geometric factors which could affect curvature suitably for compacting length and at the same time minimizing the secondary flow generation effectively are yet been not known and understood.

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