Aerodynamic Design and Numerical Analysis of S-Duct Intake

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Abstract. Design and development of air intake is one of the most crucial requirements of any air breathing propulsion system. The performance of the intake ultimately decides the performance of the propulsion system and the aircraft as a whole. Intake design affects both internal and external aerodynamic of the aircraft and hence the design problem involves a large number of variables and multiple design requirements. The current study looks into the Aerodynamic design of S-Duct intake for subsonic conditions. The study takes into consideration, two centerline and five Length-to-Offset ratios as parameters for the design. CFD analysis is conducted for all the configurations at multiple angles of attack and the corresponding data is evaluated. Total pressure recovery and Total pressure distortion coefficients are evaluated for all the configurations and the results are discussed.

Keywords: Propulsion Systems · Aerodynamics · Air Intakes · S-Duct · Subsonic · CFD · Intake Performance

1 Nomenclature

- TPR = Total Pressure Recovery
- P_{0AIP} = Total Pressure at the AIP
- P_{0a} = Ambient Total Pressure
- θ = Angle in Degrees
- $DC(\theta)$ = Total Pressure Distortion Coefficient
- P_{0mean} = Mean Total pressure
- P_{0min} = Minimum Total Pressure
- ρ = Density
- v = Velocity
- y = y co-ordinate
- x = x co-ordinate
- L = Length
- H = Offset/Height
- R = Radius
- W = Width
- a = Semi-major axis
- b = Semi-minor axis
- α = Angle of attack

B. Raj et al. (Eds.): ICETE 2023, AER 223, pp. 1226–1233, 2023.
https://doi.org/10.2991/978-94-6463-252-1_123

2 Introduction

Design and development of air intakes began as a solution for engine cooling in piston engine driven aircrafts. The advent of jet engines during the Second World War and the subsequent need to achieve supersonic flight accelerated the evolution of intake Aerodynamics. The late 1940s focused on designing intakes to handle shocks and this research led to the understanding of spillage drag which has since then proven detrimental to the design of subsonic intakes as well. The Cold War era research also led to vital understanding of various phenomena associated with intakes such as dynamic distortion and Swirling flow. Design of an intake must take into consideration, both external and internal flow phenomena where in the engine must receive the required mass flow of air at a desirable pressure and flow uniformity while not adversely affecting the aircraft's flight performance. Total Pressure Recovery and Total Pressure Distortion at the Aerodynamic Interface Plane (AIP) are most important intake performance parameters and directly affect the engine performance. For UAVs and Cruise Missiles, in order to attain high packing efficiency, it is often required to design short intakes with considerable offset. However, such designs tend to have sharp curvatures which would result in flow separation, reduced total pressure recovery and increased total pressure distortion at the AIP. The current study tries to solve this problem by designing a three-dimensional model of a Serpentine duct, considering various parameters and subjecting them to numerical analysis using CFD.

Goldsmith and Seddon discuss about the design requirements, parameters and methodology of intake for various Mach numbers and Aircraft configurations [1]. Lee and Boedicker clearly describe the importance of centerlines and area shaping. They consider three centerline line configurations and three area ratio variation coupled with Gerlach shaping to arrive at an optimum design of an S-Duct [2]. Fotios and others arrive at a design procedure for designing an S-duct for UAVs by using B-Spline for centerline and Gerlach Shaping for area variations [3]. Asghar and others studied the effect of Offset-to-Length on the performance of the intake both numerically and experimentally [4]. Luidens and others describe method to design optimum subsonic inlets. They also describe the importance of the lip geometry and explore its design procedure as well [5]. Lee and Cho investigate the effects of boundary layer suction by considering a RAE M2129 S-Duct with a semi elliptical entry face [6]. Triantafyllou and others simulate flow over an F-16 aircraft with an operating intake and compare them with experimental data [7]. Ibrahim conducted a detailed numerical study on intakes of F-5E and F-16 aircrafts [8]. Berens and conducted a detailed numerical and experimental study on S-Ducts for UAVs in collaboration with AIRBUS Defense and Space, ONERA, Swedish Defense research Agency, SAAB and ALENIA. Analysis was done for a top mounted intake for stealth applications [9]. Brandon arrived at a design of an S-Duct by comparing RAE-M2129 centerline with a centerline defined by the intersection of two circular arcs [10]. Sivapragasam and others describe in detail, various parameters to describe the flow quality while arriving at a design for a distortion generation system [11]. The details of the design and the subsequent analysis are described in the following sections.

3 Background Theory and Design Methodology

The flow inside an S-Duct changes its direction and there is a likelihood of flow separation depending on how the curvature changes. The separation is usually triggered at the first bend of the duct and hence the selection of the centerline for duct becomes a crucial factor. The centerline offset also becomes important as it ultimately decides the change in curvature along the length of the duct. These two factors are the most significant constraints while designing an intake. In order to minimize weight and increase the packing efficiency, the length has to be kept as low as possible which would result in sharp curvature changes and hence lead to flow non uniformity and total pressure reduction at the engine face (AIP). The problem becomes more involved when cross-sectional area changes are considered along the length of the duct. The area ratio between the entrance and exit of the intake affect the pressure and velocity distribution along the length of the duct and care must be taken to ensure that the area change is gradual so as to reduce the flow non uniformity to the largest extent possible. The flow inside the duct is also strongly affected by the shape of the cross-sectional areas along the length. The AIP is typically circular; however, the entrance shape of the duct must be carefully selected such that the flow does not have the tendency to separate along any of the three axes. At the entrance, the shape is typically chosen to have a lower vertical height so that the flow follows the curvature of the duct. Another factor affecting the flow quality is the cowl profile at the entrance of the duct. The cowl must be designed such that the flow inters the duct in a uniform manner for a range of Mach numbers and angles of attack. In the current study, two intake performance evaluation parameters have been studied. The parameters are Total pressure Recovery and Total Pressure Distortion. Total pressure recovery is defined as the ratio of total pressure at the AIP and the ambient total pressure. As the name suggests, this parameter quantifies the amount of total pressure getting retained at the AIP as compared to the free-stream.

$$TPR = \frac{P_{0AIP}}{P_{0a}} \qquad DC(\theta) = \frac{(P_{0mean}) - P_{0min}}{\frac{1}{2}\rho v^2{}_{AIP}}$$

Total pressure distortion is defined as the difference between the mean total pressure at the AIP and the lowest mean total pressure at a sector on the AIP at an angle θ, divided by the mean dynamic pressure at the AIP. This parameter estimates the extent of the total pressure variation circumferentially at the AIP; which gives a clear description of the flow distortion levels at the AIP. The angle θ could be 30, 45, 60 or 90 degrees. However, the angle of 60 degrees us widely used and accepted. Hence, the angle selected in the current study is 60 degrees. The geometry of the duct is governed by a centerline. Two centerline configurations have been considered in the current study and they were chosen due their dissimilarity from each other. First centerline is defined by a fourth order polynomial [2] given by:

$$y = H\left[3\left(\frac{x}{L}\right)^4 - 8\left(\frac{x}{L}\right)^3 + 6\left(\frac{x}{L}\right)^2\right]$$

The polynomial gives a centerline whose curvature changes rapidly at the entrance and gradually as the flow approaches the AIP. Flow in the duct governed by this centerline would have to accelerate along the upper edge of the first bend. However, since the change in curvature is gradual at the second bend, the flow would get a chance to regain uniformity. In the subsequent sections, this configuration will be referred to as centerline 1. The second centerline is formed by the intersection of two circular arcs [10]. Unlike the previous centerline, this centerline has constant radius of curvature throughout its length. The centerline is defined by two equations given below:

$$L = 2Rsin\theta \qquad H = 2R[1 - cos\theta]$$

This centerline is symmetric about both length and height and hence the average velocity profile would remain fairly uniform. The effects on velocity of the flow by the duct will be mostly dependent on the shape and cross-sectional area variation along the length of the duct. In the subsequent sections, this configuration will be referred to as centerline 2. A comparison of the centerlines is illustrated in Fig. 1. Centerline 1 increases the elevation of the flow more rapidly in the first half of the duct length due to influence of the fourth order term; whereas Centerline 2 continues to maintain a constant change rate because of its symmetric design.

In the current study, centerlines with multiple Length-to-Offset ratios have been used. A total of five ratios varying from 2.14 to 3.57 have been considered for both the centerlines. A constant offset has been maintained. Hence, with change in the Length-to-Offset ratio, the only change in geometry will be the length. The entry face shape decides the velocity and pressure distribution in the direction perpendicular to the duct-flow. Hence, in order to negate any non-uniform features, the vertical height of the entry face has to be low as compared to the width. On top of that, to prevent any corner separation issues, the edges must be rounded. In the current study, the entry face was designed to have an aspect ratio of 1.7 [3] and the shape of the entry face was that of a straight slot as shown in Fig. 2 (Left).

Commercially available CAD tool, SOLIDWORKS was used to generate the 3D models. The centerline was imported into the CAD tool and the corresponding entry and exit faces were sketched on their respective planes. The entry face was lofted along the centerline till the exit to arrive at the duct. This ensured that the shape and area change along the length of the duct were gradual. Figure 3 (Left) shows the lofting planes set to be perpendicular to the centerline and the duct model generated by lofting along the centerline. The intermediate lofting planes with varying shapes and areas are also highlighted in the figure.

The cowl of the inlet is one of the most important components as it is responsible for the flow uniformity at the inlet entry face. The cowl has to be designed in such a way that it directs the flow into the intake without affecting the flow direction and at

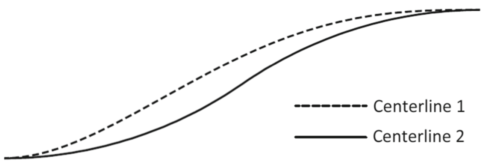

Fig. 1. Centerline Comparison

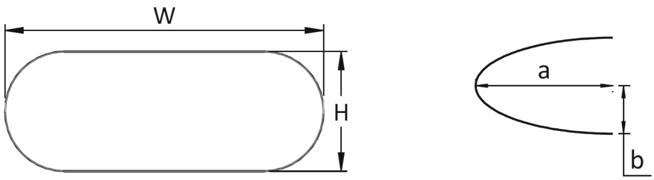

Fig. 2. Entry Face (Left) and Cowl Profile (Right)

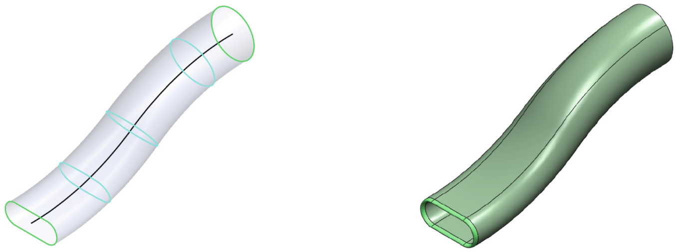

Fig. 3. Cowl Profile and Final 3D Model of S-Duct Intake

same time maintaining flow attachment externally. For subsonic and low transonic Mach numbers, the cowl profile typically resembles the leading edge of an airfoil and it can be considered as a half ellipse. In the current study, the cowl profile has been designed considering a semi ellipse with an aspect ratio of 2.5 [5].

Figure 2 (Right) depicts the cowl profile. The CAD model of the complete duct was made by sweeping the cowl profile along the inlet entry face. Figure 3 (Right) shows the inlet model with the cowl attached.

4 Discretization and Solver Setup

The domain for CFD analysis was designed such that, there exists a flat plate through which the intake duct protrudes outwards. This was done to simulate the conditions where the engine is placed inside the fuselage and the intake scoops air from the surrounding.

Discretization of the domain was done using commercially available Ansys Fluent Meshing tool. The meshes obtained were unstructured with Poly Hex core cells. $k-\omega$ SST turbulence model was used. No slip wall boundary condition was applied and the

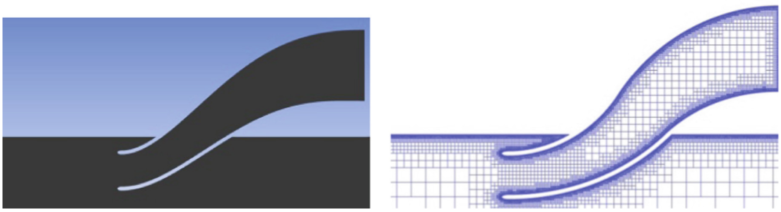

Fig. 4. Cross-sectional view of the Computational Domain (Left) and the Mesh (Right)

desired y^+ value was taken as 1. The first cell-layer height was set to $7.7 \times 10^{-6} m$ and 20 layers of boundary layer cells were considered. Figure 4 depicts the cross-sectional view of the computational domain and the mesh. Commercial CFD solver Ansys Fluent was used to solve Reynolds Averaged Navier-Stokes Equations (RANS). Density based steady solver was employed with implicit Roe-FDS flux formulation. The convergence criterion was set as 10^{-5}. Air was considered as ideal gas and viscosity variation was set to Sutherland. Pressure far-field boundary condition was used to simulate the flight conditions. The Inlet was simulated for a Mach number of 0.5 at an altitude of 5 km. Pressure outlet condition was given at the exit of the intake and static pressure was specified as per engine requirements.

5 Results and Discussion

Initial simulations were done for all five Length-to-Offset ratios for both the centerline configurations at zero-degree angle of attack in order to get a fair understanding of the performance variation. Using the data obtained from these simulations, configurations exhibiting undesirable performances could be eliminated. From the results obtained (Fig. 5) it was clear that the Centerline 2 for all the Length-to-Offset ratios had higher pressure recovery as compared to Centerline 1. Unsurprisingly, both the centerlines resulted in lower total pressure recovery at lower Length-to-Offset ratios; this is due to the fact that the flow has to change its direction more rapidly for the lower ratios than the higher ones which would in turn result in flow separation at worst and highly non uniform flow at best.

The first three Length-to-Offset ratios were no longer considered for both the centerlines due to the aforementioned reasons. For the remaining four configurations, i.e., two centerlines and two Length-to-Offset ratios, for the same free-stream conditions, simulations were done for angles of attack varying from −10 degrees to 10 degrees in steps of 2 degrees to analyze the intake performance and hence, converge on a selection of the desired intake. The solution setup was same as the previous conditions and the results were tabulated considering 3.21 as Length-to-Offset ratio (L/O) 1 and 3.57 as Length-to-Offset ratio 2. The results of the simulations were tabulated and are shown in Fig. 6.

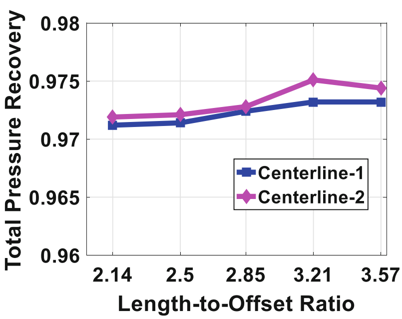

Fig. 5. Total Pressure Recovery Variation with Length-to-Offset Ratios

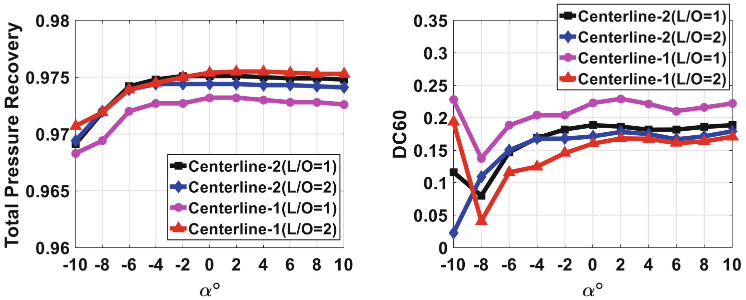

Fig. 6. Total Pressure Recovery and DC60 Variation with Angle of Attack

From the results obtained, it was observed that the total pressure recovery distribution varying from negative to positive angles of attack is not symmetrical about the zero-degree angle; in fact, it was observed that the total pressure recovery increased as the angle of attack changed from negative to positive. This demonstrated the effect; the fuselage would have on a bottom mounted intake. The presence of the fuselage body would ensure that even at relatively high angles of attack, the external flow attached to the fuselage body would reduce the flow velocity experienced by the intake which would ensure a smoother transition of the flow through the duct with increased Total Pressure Recovery. A similar phenomenon was observed for DC 60 estimations as well. However, distortion values increased with increase in angle of attack. Significantly low distortion values were observed at relatively high angles of attack like -8 degrees. This could be due to the shielding effect the fuselage would provide at negative angles. The effective angle of attack experienced by the intake would be a lot lower and the actual angle of attack.

6 Conclusion

From the data obtained, it can be concluded that although the higher Length-to-Offset ratio configurations yield better results, the increment in performance is not high enough to negate the space increment requirement. Considering both the TPR and DC60 values, Centerline 2 with Length-to-Offset ratio 1 can be deemed as the desired design.

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