

A REVIEW OF THE CHARACTERISTICS OF SUBMERGED AIR INTAKES

Leticia Hime, César Celis Pérez, Luís Fernando Figueira da Silva
Department of Mechanical Engineering; Pontifícia Universidade Católica do Rio de Janeiro; Rua Marquês de São Vicente, 225; 22453-900 Rio de Janeiro, RJ
hime@mec.puc-rio.br; ccelis@mec.puc-rio.br; luisfer@mec.puc-rio.br

Sandro Barros Ferreira
Institute of Energy; Pontifícia Universidade Católica do Rio de Janeiro; Rua Marquês de São Vicente, 225; 22453-900 Rio de Janeiro, RJ
sandro@ituc.puc-rio.br

Antonio Batista de Jesus, Viviam Lawrence Takase, Harry Tavares Maia Vinagre
Empresa Brasileira de Aeronáutica SA – EMBRAER; Av. Brigadeiro Faria Lima, 2170; 12227-901 São José dos Campos, SP
antonio.jesus@embraer.com.br

Abstract. *This paper presents a literature review of the so called NACA intakes. A large number of references were produced between 1940 and 1960, however, few of them have detailed information about the flow field. These works underline that the thinner the boundary layer which develops upstream of the inlet, the higher the efficiency obtained. More recent references regard the adaption of well known submerged inlets and its numerical simulation via CFD techniques. Among those, several were related to engine intake, at both sub and supersonic flight conditions. Regarding performance improvements, the following techniques can be found: (i) Vortex generators; (ii) Flow deflectors; (iii) Parametric geometric optimisation; (iv) Pulsating jets. A common feature to all successful performance improvement techniques is the modification of the energy content of the boundary layer which develops upstream of the inlet, which can be expected on the basis of the classical NACA reports.*

Keywords: *air inlets, transport aircraft, vortex generator*

1. Introduction

NACA intakes, Fig. 1, have been widely used in aircraft as a low drag source of external flow for air conditioning, ventilation and cooling systems. In this work a litterature review has been carried out in order to establish the state-of-the-art of these intakes. A great number of references were produced between 1940 and 1960, and regard experimental work developed at that time, all of them were conducted by the National Advisory Committee for Aeronautics.

Figure 1. Typical NACA inlet (Faria and Oliveira, 2002).

Within the whole lot of references reviewed, few of them had detailed information about the flow field, what makes the comparison between the results described and a Computational Fluid Dynamics (CFD) simulation possible. Despite the great amount of experimental work described in the references, the procedures were not always detailed.

More recent references regard the adaption of well known submerged inlets and its numerical simulation via CFD techniques. Among those, several were related to engine intakes, at both sub and supersonic flight conditions.

Regarding performance improvements, the following techniques can be found: (i) Vortex generators; (ii) Flow deflectors; (iii) Parametric geometric optimisation and (iv) Pulsating jets.

Concerning the use of vortex generators, two papers are of interest, one of them, from EMBRAER's team, employs a delta wing vortex generator. The second paper uses a different vortex generator technique, which details are not given. Formal optimization methods are fashionable tools which seem to provide interesting means to propose geometrical enhancements, but are nevertheless limited to the quality of the flow solution. A common feature to all successful performance improvement techniques is the modification of the energy content of the boundary layer which develops upstream of the inlet, which can be expected on the basis of the classical NACA reports.

The classical measures of performance of air intakes are the mass flow ratio and the ram-recovery ratio, which is the ratio between the dynamic pressure at the throat of air inlet and the freestream dynamic pressure. The mass flow ratio is the ratio of the actual mass flow ingested to the mass flow that would enter the inlet throat at freestream conditions.

Note that most recent works on novel configurations involve both experimental and modelling efforts. This is understandable, since, in the authors' opinion, the flow conditions involved are outside the domain of application of most turbulence models. Also, obtaining mesh-independent solutions is not demonstrated in the papers available.

There seems to be an oportunity for the performance improvement of secondary air inlets, which may be explored by the use of CFD techniques. However, the experimental validation of the modelled flowfields is mandatory. None of the performance enhancement techniques explored to date have shown decisive advantage with respect to the others, though, it is the authors belief that minute modifications of the turbulent boundary layer structure upstream of the inlet are more likely to succeed. In particular, local modifications to the turbulent fluctuations energy content could be devised in order to substantially alter the boundary layer development.

2. Early Works

Gault (1947) presents results for a single planform of NACA submerged inlet, which has been tested in a $1/5-$scale model of a fighter airplane. Twin inlets were located at the fuselage side immediately above the wing surface. Lip and ramp pressure and total-pressure losses were obtained as a function of angle of attack and velocity ratio. Tests have been made with retracted wing flaps and with flaps deflected 55^o, aiming at changing the pressure distribution along the wing. It was determined that low energy regions occurred near the side of the inlet, adjacent to the wing. Tests indicated that upwash was disorienting the flow perpendicularly to the centreline of the duct system. Thus, deflectors were used to avoid flow separation. Positioning the inlet further upstream would permit using smaller deflectors, and even obtaining higher pressure recoveries.

A $1/4-$scale model of a fighter-type airplane was tested with two different locations of submerged inlets (Delany, 1948). NACA inlets with deflectors have also been considered, as illustrated in Fig. 2. Different distances between the inlets of the duct and the engine have also been considered.

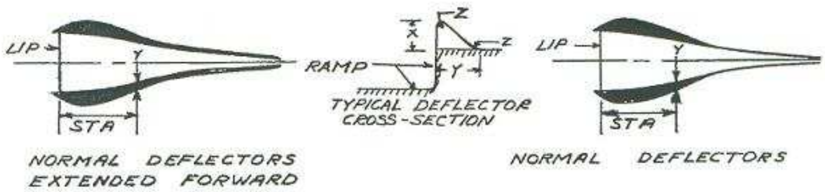

Figure 2. Schematic representation of the flow defectors (Delany, 1948).

High ram recovery has been observed for all intakes located upstream of the wing, where the boundary layer is thinner, zero angle of attack and velocity ratio 0.7 between the throat and the freestream. The effects of angle of attack on pressure recovery are small, i.e., about 0.001 per degree of angle of attack for parallel inlets and 0.005 for divergent inlets. The ram recovery measured at the duct entrance is 0.960, for divergent walls with deflector extended forward, 0.970 for simple divergent walls, and 0.890 for parallel walls. This is a singular result, since for most configurations tested the deflector increased the ram recovery about 0.005. The worst result obtained using divergent walls was better than the best result with parallel inlets. The studies of flow characteristics indicated the formation of low velocity regions near the ramp walls in NACA inlets. Tuft tests indicated that the air flow along the ramp followed the divergent walls, while the air flow along the fuselage was approximately parallel to the freestream. Consequently, at the top of the ramp walls there was a sudden change in the direction of air flow, which resulted in a rotational flow, as shown in Fig. 3

Drag results were obtained by force measurements on the complete model and measurements of momentum of the air immediately downstream the inlet. It was found that the increase in drag with the deflectors may offset the advantage in ram recovery. It is believed that flow separation occurred in the aft portion of the deflector. In order to relieve the separation, the deflectors were extended forward, which led to a 40% reduction of the drag penalty.

Hall and Dorn (1948) report an experimental investigation of NACA submerged inlets at four locations on the fuselage of a fighter airplane model for Mach numbers, M, from 0.30 to 0.875, conducted in a high-speed wind tunnel. The measurements of the boundary layer on the fuselage showed that, as the Mach number was increased, the boundary-layer thickness increased, this change is attributed to a forward movement of the laminar/turbulent transition point along the fuselage with increasing Reynolds number. The ram-recovery ratio at the entrance is greatly affected by variations in the

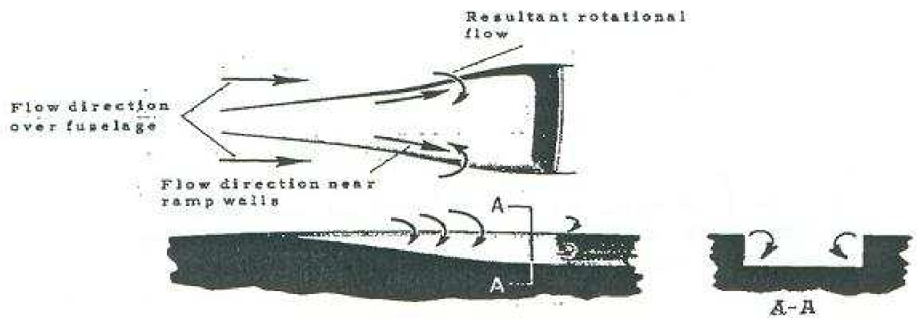

Figure 3. Schematic representation of the rotational flow along a typical NACA inlet (Delany, 1948).

mass flow ratio. The most important conclusions of the investigation were that (i) variations of Mach number and angle of attack, in general, cause small variations in the ram-recovery ratio and (ii) the increment of drag coefficient, due to the submerged inlets with deflectors, decreases with increasing mass flow ratios.

Hall and Frank (1948) present the results of an experimental investigation performed in a high-speed wind tunnel of the ram-recovery characteristics of NACA submerged inlets on a model of a fighter airplane at Mach numbers from 0.30 to 0.875. The angle of attack range of the tests was from -2^o to 6^o, whereas the mass flow ratio was varied from as low as zero to as high as 1.80, depending upon the effects of flow instability and Mach number. During the most of the investigation, the inlet lip angle was -3^o. With the inlets at the two forward locations, tests were also made with inlet lip angles of -1^o and -5^o. Four longitudinal inlet locations were investigated. The highest ram-recovery ratios were obtained with inlets in the forward location. Increasing the boundary-layer thickness decreased the ram-recovery ratio and, in general, the ram-recovery ratio decreased with increasing angle of attack. With no deflectors on the ramp the ram-recovery ratio increased greatly as mass flow ratio increased to approximately 0.60, reached a maximum between 0.60 and 0.80 mass flow ratio, and slowly decreased for greater flow rates. The boundary layer deflectors increased the maximum ram-recovery ratio and the mass flow ratio at which it occurred.

Two submerged inlets have been tested in a small wind tunnel (Mossman, 1949). The width of the inlet is such as that interference of the flow characteristics over the inlet and the tunnel is observed. Due to the difficulties of experimenting at transonic speeds, the results of the paper are not accurate. However, a qualitative analysis can be achieved. These inlets had a width-height ratio of 4.2 and ramp angle of 7^o. One inlet had parallel ramp walls, whereas the other had divergent ramp walls. The range of Mach number was 0.2 to 0.94, for the parallel ramp inlet, and 0.2 to 0.96 for the divergent ramp inlet. The divergent inlet works better at higher Mach numbers, with satisfactory pressure recovery, than the parallel inlet. This was found to be due to the difference in the boundary layer characteristics over the ramp. The highly three dimensional flow through divergent inlets leads to a slower growth of the boundary layer, when compared to the quasi-two dimensional flow found in parallel inlets. For both inlets the decrease of ram recovery with decreasing of mass flow ratio was attributed to the thickening of the boundary layer, which was a consequence of adverse pressure gradients along the ramp.

The results of the parallel inlet indicated that, at Mach number about 0.8, a weak shock wave is formed at the beginning of the ramp, which extended a short distance along the ramp and coincided with the thickening of the boundary layer. Divergent inlets at Mach 0.94 show shock waves at two locations along the ramp. Oblique waves appear at the beginning of the ramp and a normal wave at 70% of the ramp length. At higher freestream Mach numbers, and for mass flow ratios greater than 0.6, this normal shock wave can be strong enough to cause separation and, consequently, ram recovery decreases.

Axelson and Taylor (1950) describe the wind tunnel tests of a NACA submerged inlet in transonic flow, for Mach numbers between 0.7 and 1.15. The inlet was placed at a transonic bump, which consists of a plate with one profiled side, at inlet, and one flat side, at the duct exit. The profiled side of the bump makes it possible to reproduce the conditions of the aircraft at a given angle of attack. In this work three models with different angles of attack, 0^o, 4^o and 8^o, have been built. The results demonstrate the influence on ram-recovery of the inlet mass flow, boundary layer and freestream Mach number. Pressure and mass flow contours suggest the causes of the measured losses, and even the probability of formation of vortices at the wall deflection. A particular result deserves discussion. When the angle of attack is increased from 0^o to 4^o, the ram recovery decreases about 0.05. However, when the angle of attack is increased from 4^o to 8^o it increases 0.02. This result contradicts other experimental works (Delany, 1948), where the ram recovery always decreases with the angle of attack. The main conclusion of this paper is that the losses are asociated to the boundary layer thickness. The thinner the boundary layer, the higher is the energy content, hence, the higher the ram recovery.

Frank and Taylor (1951) compare the transonic characteristics of a scoop-type inlet and a NACA submerged inlet.

Wind tunnel tests have been made for both geometries at the same conditions, i.e., inlet shape, exit form and the bump on which they are built. Tests have been performed in a range of Mach numbers from 0.79 to 1.12 and the angles of attacks are 0^o, 3^o, 6^o, 9^o. In order to provide different mass flow ratios, a constriction on the exit area has been used.

At low angle of attack the submerged inlet had higher or equal ram recovery than the scoop inlets. It is believed that this is due to the thicker boundary layer upstream to the scoop inlet, when compared to the thinning of the boundary layer along the ramp of the submerged inlet. However, as the angle of attack is increased, the submerged inlet performance decreased sharply. Also, as the Mach number increased, this decrease began at lower angles of attack. Tests with thicker (tripped) boundary layer indicated that the losses in ram recovery and mass flow ratios were greater for the scoop inlet. The mass flow ratio of the submerged inlet was practically unchanged when under thicker boundary layer. The increment of external drag was determined by the difference between the drag of the solid body with and without the inlet. Internal drag was subtracted from the total drag. The drag coefficient was always larger for the scoop inlet.

James and Schlaff (1951) obtained comparative drag and pressure-recovery data for a submerged inlet and a nose inlet model in the transonic speed range. The investigation was conducted over a mass flow ratio range from 0.4 to 0.8 and a Mach number between 0.8 and 1.10 employing large-scale recoverable free-fall models, released from a carrier airplane from about 40.000 feet pressure altitude and accelerated in free fall to a Mach number between 1.10 and 1.15.

The results showed that the external drag of both inlet models increased slightly with increasing mass flow ratio, which is in reasonable agreement with previous researches. Pressure recovery decreased above a Mach number of about 0.9, at lower mass flow ratios. This decrease of pressure recovery increased proportionally to the decrease of mass flow ratio. Also, the maximum entrance pressure recovery of the submerged inlet occurred at a mass flow ratio of about 0.6 for the freestream Mach number range between 0.8 and 1.05.

The investigation concluded that the maximum pressure recovery of the submerged inlet model, at subsonic speeds, and the variation of pressure recovery of the submerged inlet with mass flow ratio at subsonic and supersonic speeds are in reasonable agreement with previous wind-tunnel results (Mossman and Randall, 1948; Frank, 1950).

Anderson and Frazer (1952) investigate the behavior of NACA inlets in supersonic speeds, in a Mach number range from 1.17 to 1.99. The model used was the same $1/4-$scale model used by Delany (1948) . Inlets with round lips and sharp lips have been tested. The sharp lip has been used in an attempt to yield higher mass flow ratios. The round lip inlet has been tested in a Mach number range up to 1.26. Results showed that the effect of the lip shape is small. Schlieren images showed a nearly normal shock wave present on the ramp immediately upstream to the entrance for all Mach numbers, up to 1.58, when the shock wave became attached to the sharp lip at the maximum mass flow ratio. The acceleration of the flow along the ramp leads to a decrease in maximum mass flow ratio obtainable. As the Mach number is increased this effect is less severe. It is believed that flow separation was occurring near the duct entrance for low mass flow ratios and that, when the Mach number was increased, the tendency of separation was reduced. At high mass flow ratios, the separation point moved forward and did not reduce the effective area of the duct entrance, which could lead to a sonic throat at Mach number below 1.58. At Mach numbers higher than 1.58 the shock wave moved into the diffuser and limited the mass flow ratio.

Taylor (1952) presents a comparative analysis of measurements of drag and pressure recovery for a NACA submerged inlet and two side-wall modifications on it. The investigation was conducted in a high-speed wind tunnel over a mass flow ratio range from 0 to 0.93 and a Mach number between 0.8 and 1.11.

Ram-recovery data indicated that vortices formed above the diverging ramp walls, which entrained low-energy body boundary-layer air, resulted in reduced pressure recovery. The vortices are beneficial for their influence in thinning the boundary layer along the ramp floor, but, upon, entering the air-induction system, they cause total pressure losses. It was hypothesized that increasing the angle between the body contour and ramp wall would reduce the strength of the ramp-wall vortices and displace them outwardly. Thus, the NACA submerged inlet was modified by increasing the angle between the ramp floor and walls to 134^o and 146^o, as shown in Fig. 4.

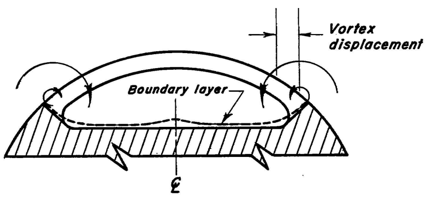

Figure 4. Schematic representation of the 134^o inlet (Taylor, 1952).

The results obtained indicated that the modified versions generally yield higher ram-recovery ratios than the NACA submerged inlet at the highest test mass flow ratio, about 0.88. This improvement in ram recovery is believed to be due to the outward displacement of the vortices generated by the ramp walls, and the leakage of accumulated ramp-wall boundary layer which passed outside of the entrance. Regarding the effects of Mach number and angle of attack, the comparisons indicated that, for all angles of attack and Mach numbers tested, the two modified inlets generally yielded equal or superior pressure recovery. Concerning drag, for the mass flow ratios of about 0.88, no significant changes resulted from the modifications for Mach numbers below 1.0, but small increases in drag accompanied the gains in ram-recovery ratio due to modifications at supersonic Mach numbers, for the higher angles of attack.

Dennard (1957) tested several auxiliary air inlet shapes in a wind tunnel through a Mach number range from 0.55 to 1.3. The results underscore the influence on pressure recovery of inlet duct inclination, yaw angle and mass flow ratio. Two shapes of flush inlet were tested; the first has parallel ramp walls, whereas the second divergent ram walls (NACA inlet). The flush inlets have a width-height ratio 4 and are followed by a constant cross section duct.

The duct inclination was varied between 15^o and 90^o. The 15^o inlet presents a pressure recovery 6% higher than the other different inclinations for $M \leq 1$. The 15^o NACA inlet has undergone several modifications. The upstream corner of the ramp and the inlet lip have been rounded and the ramp angle has been reduced to 7^o. The gains with the rounding were small, but the ramp angle change was effective for subsonic flow.

When comparing the results obtained for parallel and divergent ramp walls inlets for several mass flow ratios, it is noticeable that the divergent inlet leads to higher pressure recoveries for mass flow ratios smaller than 0.5. In order to characterize the flow topology as it approaches the inlet, some inlets were equipped with static pressure orifices. For supersonic flows, the tests show that divergent walls increase the local velocity and may yield shock waves.

3. Recent Progress

Based on the references available to the authors, a gap has been observed between the mid 1950's and the end of the 1990's. No publications could be found in this interval. The work done on the 1940's and 50's is, as expected, focused on experiments. With the development of Computational Fluid Dynamics (CFD) techniques and the increasing computational power, the late developments involve most often both experimental and numerical efforts. This section highlights the research carried out on submerged intakes from 1994 to 2004.

Farokhi (1998) discusses the concept of the so called Smart Vortex Generator and its variant, the Smart Tetrahedral Vortex Generators, shown in Fig. 5, and their application in gas turbine design. The aim is to avoid losses that commonly

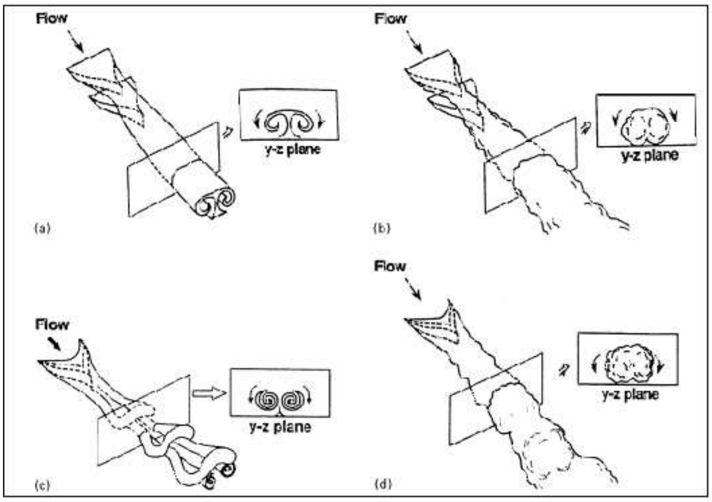

Figure 5. Flow structure downstream of doublet and wishbone vortex generators. (a) Doublet VG in laminar boundary layer; (b) Doublet VG turbulent boundary layer; (c) Wishbone VG in laminar boundary layer; (d) Wishbone VG in turbulent boundary layer (Farokhi, 1998).

affect the engine performance, mainly during its off-design operation. Results are shown for the application of the STVG on an airfoil and a nozzle.

Regarding the experiments carried out for a nozzle, pressure sensitive paint flow visualization was conducted in a two-dimensional convergent-divergent supersonic nozzle. A 60^o cavity VG, with an 8^o bottom plate ramp angle was placed on the nozzle and its pressure ratio, NPR (Nozzle Pressure Ratio) was varied from 2 to 10. The main aspects of interest are: a) there is shock formation in the low NPR cases (from 2 to 4); b) vortex cores which are generated near the vertex curve fade shortly after they are created by the edges of the cavity; c) vortex interaction with the shock pushes the shock front further downstream, and; d) the area of the cavity center experiences a high pressure zone in response to dipping streamlines which create compression waves.

Smart Tetrahedral VGs, STVGs, have been applied to a NACA 4415 airfoil. A STVG is a ramp type vortex generator equipped with a pneumatically controlled bladder which adjusted the VG height through a closed loop control system. The measured reduction in drag coefficient is quite small, whereas the increase in the lift coefficient is indeed significant for attack angle above 8.7^o.

Computational analysis of NACA air inlet, designed aiming maximum pressure recovery, with a delta wing vortex generator is described by Faria and Oliveira (2002) . The geometry considered was a flat plate of 10 m length with the NACA inlet in the centre. The calculation domain was a semi-sphere with 10 m radius, where freestream conditions are established. The mesh used is all composed by tetrahedrons warranting that y^+ is lower that 500. The conventional inlet has been simulated using Computational Fluid Dynamics (CFD) and the results obtained were similar to the expected at the design point, in terms of pressure recovery. This result was used as baseline configuration for the results with vortex generators. Modifications in the basic vortex generator, shown in Fig. 6, were also tested, regarding surface area, inclination and axial position.

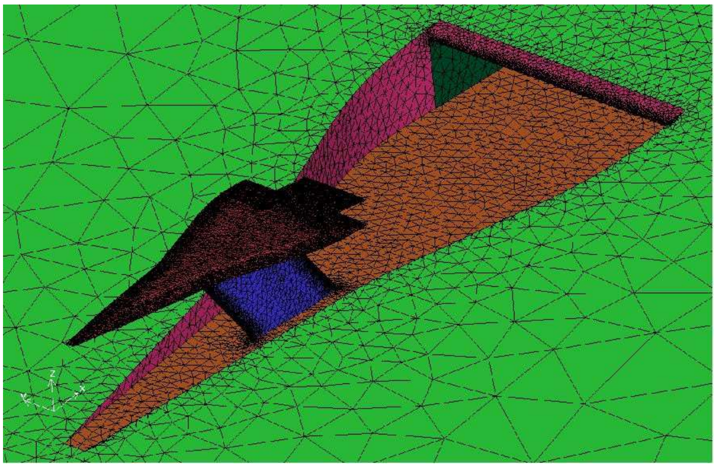

Figure 6. NACA Inlet with delta wing vortex generator (Faria and Oliveira, 2002).

The results obtained were not satisfactory. The ram recovery decreased 5 to 23% when compared with the inlet without vortex generator. The drag increased 25 to 53%.

Devine et al. (2002) investigate, both computationally and experimentally, the influence of a pair of vortex generators, which the geometry is not presented, placed upstream of an inlet, such that the NACA inlet lies downstream the merging of the vortices. The ram recovery obtained is low when compared with other data published. It is believed that it occurs because the boundary layer thickness is 1.42 times the inlet depth, which is a high ratio. The RNG $k-\epsilon$ turbulence model was used in the computations.

The vortex downwash leads to a thinning of the boundary layer and higher energy air is forced into the inlet. Results, both computational and experimental, show a increase of 34 to 37% in ram recovery. At high velocity ratios it is possible that the vortexes formed travel downstream the inlet, decreasing the ram recovery.

Taskinoglu and Knight (2002) investigated the flow of air vehicle submerged inlets through the use of numerical simulation. The work considered a generic inlet configuration only shown in Fig. 7. The flow solver adopted was GASPex,

Figure 7. Generic contoured submerged intake (Taskinoglu and Knight, 2002).

turbulence was modelled by the Wilcox $k-\omega$ model. The investigation was conducted considering, as freestream conditions, $p =$ 73 kPa, $T = 273$ K and $M = 0.7$. Numerical analysis was performed for two cases corresponding to different back pressure values. Firstly, the downstream boundary at the diffuser outflow employed a fixed back pressure of 73 kPa (Case I) that corresponds to the freestream static pressure; and secondly, a fixed back pressure of 80 kPa (Case II) was specified which was chosen to be a little higher that the freestream static pressure for the purpose of decelerating the flow. It was observed that, when back pressure is low enough for the flow to accelerate to supersonic speeds, a shock boundary layer interaction occurs at the upper wall of the inlet. This creates flow distortion and total pressure loss of 30% downstream of the upper duct. If the back pressure is increased in order to maintain the flow upstream of the duct at subsonic speeds, the high back pressure decelerates the flow on the lower part of duct and the flow escapes to the low pressure region by swirling along the side walls. This, too, leads to a boundary layer separation and flow distortion in the downstream part of the upper duct. It should be noted that total pressure loss in this case is almost half of Case I. However, the distorted flow region is more scattered and larger.

Taskinoglu et al. (2004) applied an automated shape optimization to a submerged subsonic inlet of an air vehicle, which is schematically shown in Fig.8, in order to obtain higher quality of air flow at the compressor face. The chosen

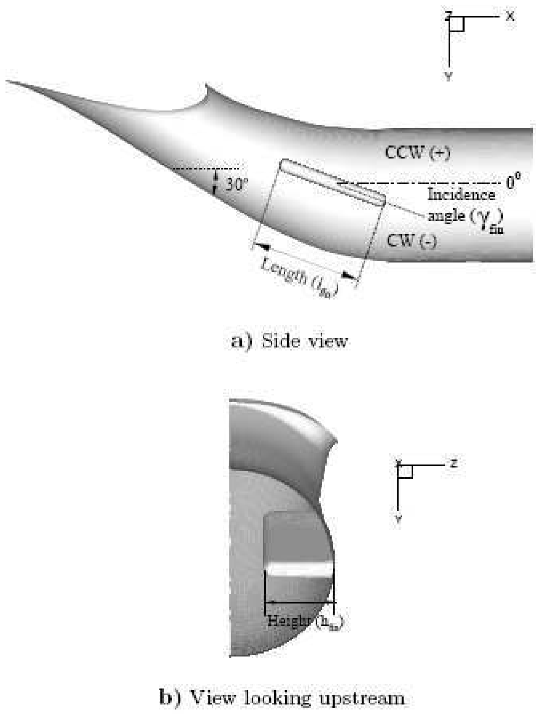

Figure 8. Parameters used on the intake optimization (Taskinoglu et al., 2004).

measures of air flow quality are the flow distortion and the swirl. For a wide range of possible geometric deformations of the baseline geometry, the deformation of the rectangular fin dimensions on the inlet channel was found to be promising for achieving a lower distortion and/or swirl index at the exit cross section of the channel. Therefore, the design variables of the optimization process are chosen to be the height, the length and the angle of incidence of the fin.

The flow solver used was GASPex, Version 4.1+, which solves the Reynolds-averaged compressible time dependent Navier-Stokes equations in three dimensions. Turbulence was modelled by the Wilcox $k-\omega$ model. The computations are started impulsively from the adopted freestream conditions, i.e., $p = 99.75$ kPa, $T = 287$ K and $M = 0.15$.

Computational results for baseline inlet, i.e., without the fin, given along the channel section and at the exit plane of the inlet duct, indicate that the change in total pressure at the exit cross section is within 1% only. However, the variation in velocity at the exit plane is almost 60%, indicating a high flow distortion. The optimization study led to two optimal inlets, dubbed A and B. These optimum inlets have fin height and fin length in the range of 9 to 12 mm, and 18 to 24 mm, respectively, and that the angle of incidence is the main parameter which determines the value of the swirl index. A fin protrusion with a positive incidence angle, as is the case of optimum inlet A, creates a high pressure region over the upper surface of the fin. The pressure differential between lower and upper surfaces of the fin causes the formation of a tip vortex with counter clockwise circulation, which therefore accentuates the swirl, although creating a more axisymmetric flow field, and hence lower distortion. A fin protrusion with a negative incidence angle, however, creates a lower pressure region on the upper surface of the fin, resulting in a tip vortex formation in the clockwise direction, opposite to the swirl direction of the baseline inlet, which reduces the swirl. The improvements obtained in this case with respect to the distortion level were not as good as in the previous case.

The experimental portion of the inlet optimization problem was conducted in a subsonic wind tunnel. All the data were collected using rotating Pitot rake connected with pressure acquisition system. Comparing experiment and computation, for the baseline inlet case, reasonable agreement was obtained in the low velocity region associated with flow separation of boundary layer due to the duct curvature. Also, the maximum velocity values and velocity range are in very good agreement. However, there are some discrepancies between experiments and computations in the high velocity region, which are the subject of further investigation. A similar situation can be seen for the optimal inlets.

4. Acknoledgements

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