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VARIABLE FIDELITY DESIGN OPTIMIZATION OF AIRCRAFT AIR INTAKE

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ABSTRACT

The aircraft air intake is one of the most important parts in the layout design of modern fighter and trainer aircraft. Most of the aircrafts famous for their good maneuvers have a well designed air intake, which is capable of tolerating high angles of attack and large sideslip angles without significant pressure losses.

The aim of the present work is to optimize the layout of subsonic S-type air intake using seven design parameters through two optimization cycles. The first optimization cycle uses analytical representation of the cost function denoting the total pressure loss in the air intake, and also the physical and geometrical constrains imposed on the design for a complete geometrical compatibility with the external shape of the aircraft. Such representation invokes low fidelity techniques. A genetic algorithm was used for the optimization to obtain an optimal shape of the air intake.

The obtained results were used as the initial point for the second optimization cycle based on CFD analysis of the problem, which signify a higher fidelity computational technique. The complete optimization cycle is originated by integrating together all the developed modules, from geometry and grid generation to the final convergence of the solver solution and global optimization.

KEY WORDS

Air intake
Optimization
Variable fidelity
Pressure loss
CFD
Genetic Algorithm

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NOMENCLATURE

σ Total pressure recovery
CFD computational fluid dynamics
H_{diff} the diffuser height and it is typically the intake height defined from the general Layout
L_{diff} the diffuser length and can be obtained by subtracting the available components lengths from the over all intake length defined from the general layout
RCS Radar cross section
GA Genetic Algorithm
σ The flow total pressure recovery
Z the z coordinate of the intake centre line
X the x coordinate of the intake centre line

INTRODUCTION

The air intake in the fighter or trainer aircraft is the part responsible for delivering the free stream to the engine, and retards it to convert its kinetic energy into pressure, with maximum pressure recovery and minimum flow distortion. Numerous studies have been conducted on various types of intakes [1-8], but it seems that most of the work is confidential so few of those publications are available [8]. Most of the modern aircrafts and cruise missiles implement S-type intake to properly allocate the engine thrust in a location and constrain the inlet capture face to another location shifted in the vertical or side direction by a distance, this can also improve the stealth of the aircraft by hiding the engine compressor face which have a main contribution to the RCS. In doing so the intake duct must bend, as a result a cross stream pressure gradient will induce secondary flow along wall increasing the probability off flow separation, that is why studying the intake performance is a critical phase in engine performance and life time, since the flow distortion affects the engine life time [4], and the pressure loss affect the thrust, it is reported that 1% loss in total pressure recovery typically results in 1.6% loss in net installed thrust of a turbojet engine [5]. One way of improving the intake flow quality and minimize the pressure loss is to implement the shape optimization [1-3]. Variable techniques for optimization are available in the literature [10] but the genetic algorithm [9] for the low fidelity cycle was selected, this is because it is an algorithm capable of handling mixed discrete and continuous variables, it searches the domain without being trapped in a local minimum and it doesn't acquire a starting point. In the high fidelity cycle the direct non gradient Simplex algorithm is used [11], in combination with the CFD to obtain the value of the fitness function, which is in our case the total pressure loss, this algorithm is fast and robust but may be trapped in a local minimum that is why the aim of the first optimization cycle is to obtain an optimal value to be a base line for the high fidelity cycle optimizer. The MATALB and PYTHON programming languages in combination with the powerful modular ESI-CFD multi-physics flow simulation software package were used to automate the two cycles, all the design experience and geometrical and performance constrains of the practical air intake design cycle were impeded in the developed modules. An actual turbofan jet engine data was used to develop an optimized air intake using the techniques developed here. The obtained optimal shape can be thoroughly analyzed from all aspects of performance and if needed a wind tunnel model and test can be used to verify the results obtained from the CFD simulation of the flow inside the arrived optimal intake.

PROBLEM FORMULATION AND VARIABLES DEFINITION

To be able to represent geometrically the air intake of S-type some geometrical parameters were selected and used in both optimization cycles those variables are
Lip length, the length of the constant area duct after throat, the length of the constant area duct after diffuser, the inlet capture face shape “elliptical or filleted rectangular “which is considered a discrete parameter”, the inlet capture face aspect ratio, the fillet factor and the center line parameter which is also a discrete variable, these variables are graphically illustrated in Fig.1.

It is clear that the first three parameters are lengths and the following three parameters totally represent the cross section of the intake, and the last parameter represent the lofting mean curve of the diffuser which is represented by one of four equations, typically are,

$$Z = \frac{H_{diff}}{2} \times \left(1 - \cos\left(\frac{\pi \times X}{L_{diff}} \right) \right) \tag{1}$$

$$Z = H_{diff} \times \left(3 \times \left(\frac{X}{L_{diff}} \right)^2 - 2 \times \left(\frac{X}{L_{diff}} \right)^3 \right) \tag{2}$$

$$Z = H_{diff} \times \left(4 \times \left(\frac{X}{L_{diff}} \right)^3 - 3 \times \left(\frac{X}{L_{diff}} \right)^4 \right) \tag{3}$$

$$Z = H_{diff} \times \left(6 \times \left(\frac{X}{L_{diff}} \right)^2 - 8 \times \left(\frac{X}{L_{diff}} \right)^3 + 3 \times \left(\frac{X}{L_{diff}} \right)^4 \right) \tag{4}$$

The above mentioned equations all satisfy the horizontal tangency condition at both the start and the end of the curve.

The required data to continue the geometrical representation are the total intake length, and the total intake height, which are considered as constrains on the design imposed from the general layout of the complete aircraft.

Before starting the design of the intake the aircraft design point and engine data are important information to be supplied, in our study the design point Mach Number is 0.7 and the design point altitude is 6069 meters, the engine in use is the Allied Signal GARRETT TFE 731-2A-2A modular turbofan.

The first step before entering any lower or higher fidelity cycles is to construct the geometry which is considered a design phase subject to geometrical and performance constrains.

This design has many steps which are summarized as follows

- Based on the design point and the given engine mass flow rate at this point the Throat and capture areas are calculated under the constrains that a minimum area that satisfy the mass flow rate at design point, and that no choking is to happen at any off-design point, which is an iterative procedure.

- the inner lip of the intake is selected to be a quarter ellipse with power 2.2 with the semi major axis equal to the distance between the throat and the capture sections which is one of the parameters, the ellipse semi minor is governed by the area contraction η, which is taken 1.24.
- The outer lip is designed with the target of preventing the flow from accelerating to a critical mach number, at which the drag will rise suddenly and if accelerated more can create a shock wave on the outer cowl, so the outer lip is selected to be NACA1 profile scaled by two factors, one of those factors is freely selected, but the other one must be calculated to achieve the constrain mentioned above. The obtained profile of the NACA1 is illustrated in Fig.2
- In the diffuser design step the area distribution is calculated based on the assumption of constant incremental total pressure loss distribution, which have the benefit of reducing the probability of flow separation due to expansion. A subroutine for diffuser surface generation is constructed, in which the total pressure recovery is first estimated, the diffuser is then divided into N equal sections that satisfy a smooth layout, given area distribution, required mass flow rate and the given mean line shape. Another subroutine was constructed to calculate the equivalent losses based on the constructed geometry and using empirical conical diffuser charts. Looping between those two subroutines in the main program, under the condition that the error in diffuser pressure recovery is minimum, the diffuser design is done and it's losses is calculated in the same step. For the given engine and design point the area distribution obtained is shown in Fig.3, and the Mach number distribution in Fig.4.
- Two constant area ducts are added after and before the diffuser to unify the flow entering the diffuser and engine if it was disturbed for any reason, but friction losses arise, so the longer the ducts the better the flow quality but the losses is higher, so their lengths are considered as optimization parameters. The losses in those ducts are calculated using hydraulic duct losses.
- The two bends at the start an the end of the diffuser will produce additional losses due to the turning of the flow, an equivalent losses is calculate for those bends and it is function in the angel of turning of flow and the radius of curvature.
- The total intake recovery is calculated as

$$\sigma_{total} = \sigma_{diffuser} * \sigma_{after\ throat\ duct} * \sigma_{after\ diffuser\ duct} * \sigma_{before\ diffuser\ bend} * \sigma_{after\ diffuser\ bend} \quad (5)$$

And the total pressure loss factor = 1- σ

All the above steps for designing the intake are programmed using the MATLAB scripting programming language, then collected in one main code that accept the seven design parameters, and perform the intake design steps to generate the intake surface as curves, then calculate its performance in terms of the looses in the total pressure. This code is compiled as an executable file to be used in the two optimization cycles. Final sample geometry as plotted by MATLAB is illustrated in Fig .1.

All kinds of geometrical and performance constrains are impeded in this code, any design experience that can be interpreted as equations or constrains can be also added in this step, which should insure that any seven given parameters can produce a feasible intake design that satisfy the engine demand at any flight condition, and be conformal with the general layout of the aircraft to maintain the drag in it's minimum acceptable limitations.

LOW FIDELITY OPTIMIZATION CYCLE

In this cycle a genetic algorithm is used in combination with above developed modules to obtain an optimum intake shape.
The genetic algorithm (GA) is an optimization and search technique based on the principles of genetics and natural selection. Some of the major benefits from using the (GA)

- Optimizes with continuous or discrete variables
- Deals with a large number of variables
- Doesn't require derivative information
- Is well suited for parallel processing

The genetic algorithm is here used in combination with the above code to optimize (minimize) the total pressure loss "fitness function". The GA searches the entire domain defined by upper and lower limits for the parameters, seeking an optimal intake. Those limits for the parameters are also considered to be constrains imposed from the layout of the entire aircraft or just to prevent the optimizer from exploring non practical zones of the solution domain.

The MATLAB programming language is again used to construct the optimization module and to adjust the variables limitation, the design modules and the optimizer module is compiled together in one executable file that accept variables limitations and GA optimizer settings " mutation percentage, number of generations, Number of individuals in each generation …. Etc", and produce an optimal intake.

After running the optimizer with 50 generations and 200 individual in each generation, the genetic algorithm converged to an optimal shape and the results are shown in table.1, in which the total pressure loss is calculated as a percentage of the free stream total pressure.
Finally the MATLAB surface representation of this optimal is shown in Fig.5.

HIGH FIDELITY OPTIMIZATION CYCLE

In this cycle commercial CFD package CFDRC developed by ESI group is used for the flow simulation inside the intake to obtain a more accurate estimation of the total pressure loss, PYTHON programming language which is a famous open source code programming language is also implemented to automated the following steps,

- Geometry acquisition and model building up
- Grid generation and boundary conditions setting
- Setting up and running the solver
- Analyzing the results to obtain the fitness function

This language is a high level scripting language which is very powerful in controlling windows based programs, and has a good computational capability. A discussion of the step by step procedure implemented in this cycle is to be explained here.

Geometry Acquisition and Model Building Up

The CFDRC package contains the GEOM module for geometry and grid generation and is fully controlled by the PYTHON programming language, In this step a main optimization code developed by PYTHON language calls the intake design executable file to construct the surface for the intake defined by the set of variables, the output of this phase is a set of curves defining sections of the intake at given stations, those sections are imported in the GEOM an a lofted surface is generated from those curves to construct the intake surface.
Since the S-type intake implemented her has the advantage of symmetry and in our optimization no angle of side slip will be considered in the solution of the intake, so half of the geometry is imported and symmetry boundary conditions are applied. This will help in reducing the computational cost of solving the entire intake.

Grid Generation

The automated structured grid generation in this work was considered the most challenging, since all the grid parameters need to be carefully set during the python code building up to obtain an automated grid that guarantee convergence of the solver for any given grid. The module GEOM in the CFDRC package was used to generate the volume grid. The grid file was reconstructed three times to adjust the grid shape for the solver to guarantee convergence. A sensitivity analysis for the grid parameters was conducted to assure the fastest convergence for the solver, a grid resolution density factor was defined so that the grid size is controlled in the whole domain and if this factor decreases the grid will condense relatively in all the space of the model.
The solution was started for testing with 90,000 grids in the entire domain and by decreasing the grid resolution factor the overall grid number was increased step by step, and by monitoring the solver convergence it was noted,

- Increasing the grid will increase the output accuracy
- Increasing the grid increases the truncation error and affects the solver stability at too condensed level of grid above 400,000 grids. For the internal grid inside the ducts increasing the grid will reduce the face angle and if this value drop below 20 degree unexpected instability in the solution appear, so a limit of 250,000 grid was enough and if the grid is increased no guaranteed convergence for any shape.
- The grid needs to be packed more where expected gradients of the flow is higher or near boundaries, this action affects the grid aspect ration and in turn affect the solver stability so constructing a grid of a good quality near the boundaries for any shape is an exhaustive task and needed extreme attention.

An imaginary duct for the flow entering the intake and surrounding the outer lip was meshed using coarse grid with clustering near the solid boundary to enable capturing the effect of the outer lip on the flow entering the intake, which will be more clear if

angel of attack for the flow were implemented or when a low speed flow enters the intake, which can be thoroughly analyzed for the obtained optimum intake.
The edge segmenting and clustering used here is illustrated in Fig.6. The volume grid was divided into 5 zones to facilitate the meshing and to be able to control the clustering more precisely, and if parallel processing is to be implemented this will be of a great help to divide the problem on multiple processors. The divided zones are illustrated in Fig.7.

Setting up and Running the Solver

The solver used here is the CFD-ACE module which is a finite volume pressure based solver and support multi physics problems. The spatial domain is discretized and solved using UPWIND scheme, the solver implement conjugate gradient squared + preconditioning for the solution. Inertial relaxation for the velocity and pressure were used to improve the stability of the solution. The boundary condition for the inlet flow is set to the static pressure, velocity and temperature at the given design point and no angle of attack or side slip was introduced, the boundary condition at the outlet at the engine face is the static pressure which was set to a value of 52,000 N/m^2 . The entire domain initial conditions was set to the free stream values, It is to be noticed that the angel of attack and side slip can be considered by setting the value of the Y and Z components of the velocity other than zero to define the angel of flow, which was not introduce here to limit the time of the complete optimization cycle to practical levels.

Running the Optimization Cycle

In this final step all the developed modules are linked together in one complete cycle that starts by running the low fidelity cycle to obtain an initial optimal which is then used as a base line for the high fidelity optimization cycle that implement the Simplex optimization technique, which is a low cost non gradient optimization technique suitable for the CFD problems, and is implemented in the ESI-CFD- Simulation manger module. The PYTHON language is here used to glue all the developed modules and automate the optimization cycle.

PARAMETRIC STUDY

The obtained optimal from the genetic algorithm is used as a base line in the CFD parametric study to be able to understand the effect of each parameter on the intake performance, each of the variables was changed alone while maintaining the other variables constant and equal to the optimal value obtained by the genetic algorithm.
After running the solver the results where filtered and illustrated in Fig.8, in which the effect of the first three parameters is clear, increasing the constant area duct after and before the diffuser has an negative effect on the total pressure loss this was expected due to the skin friction but in our study the turbulence of the flow was not modelled and if it was done the effect of these parameters would have been different. The lip length and inlet face aspect ratio effect was not expected because it’s more complicated but it is clear from the Fig.8 that increasing the lip within the constrained values has a positive effect of reducing the total pressure loss. The effect of the inlet face aspect ratio is illustrated in Fig.9, it clear that for the given configuration a minimum losses appear at an inlet aspect ratio of 0.6 which is not necessary the same for any other combination of the variables, but it is just to illustrate the effect of each variable isolated.

Finally what is lift is the effect of the discrete variables, which is illustrated in table.2
It is clear that the centreline equation (3) has the lowest total pressure loss among the other equations which was difficult to predict using any analytical method, also the inlet cross section type of the ellipse has a better performance over the rectangular filleted one, it is also to be noted that the interaction between those parameters are so difficult to foresee, that it why the process of parametric optimization is implemented here to seek the optimal shape.

OPTIMIZER RESULTS AND CONCLUSION

After running the high fidelity cycle optimizer the problem converged to and optimal design the results is shown in table.1, in which a comparison between the low fidelity cycle results and the high fidelity cycle result is illustrated.
It is noticed that the pressure loss value of the high fidelity cycle is higher than the value obtained from the low fidelity analysis, which is due to the higher accuracy of losses prediction in CFD.
The total pressure sections and surface contours for the optimal intake are illustrated in Fig.10 and Fig.11, the exit section Mach number contours plot are illustrated in Fig.12 and the velocity magnitude and direction vector plot for the lip is shown in Fig.13. , the mach number contours for the flow around the lip is shown in Fig.14
It is although noticed that the exit mach number obtained from the low fidelity analysis illustrated in Fig.4 has a value of .4 which agree with the average value of the mach number at exit section illustrated in Fig.12, which indicate that the techniques used in the design cycle analytical method is of partial agreement with CFD results.
Finally it was demonstrated that a complete automated cycle of geometry optimization low fidelity cycle, followed by a high fidelity CFD optimization cycle can be a powerful tool to design an optimal air intake for a fighter or trainer aircraft.

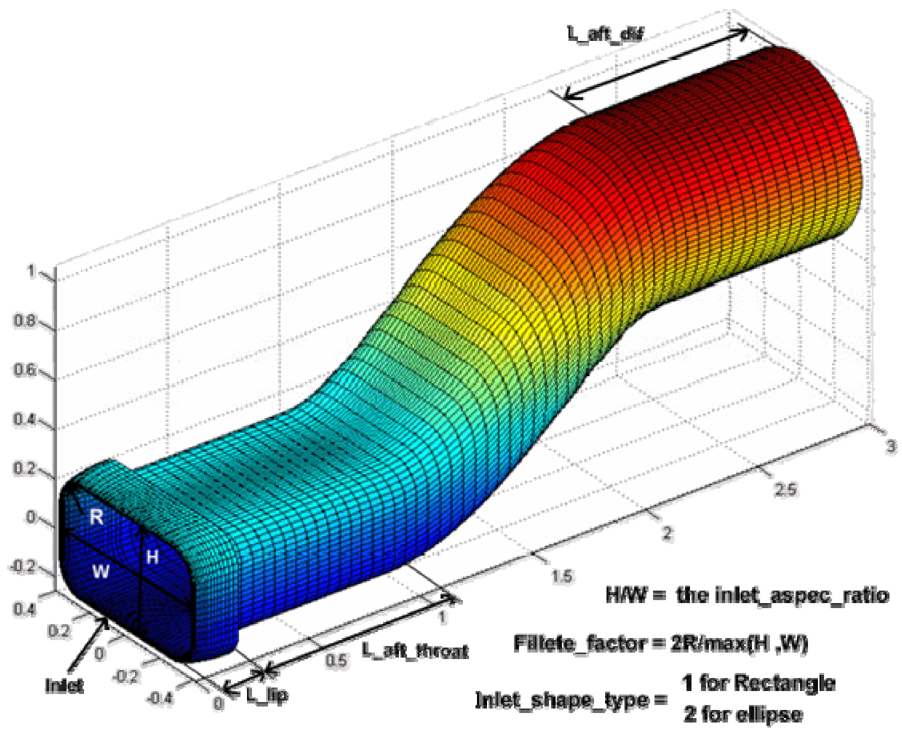

Fig.1. Intake variables illustration

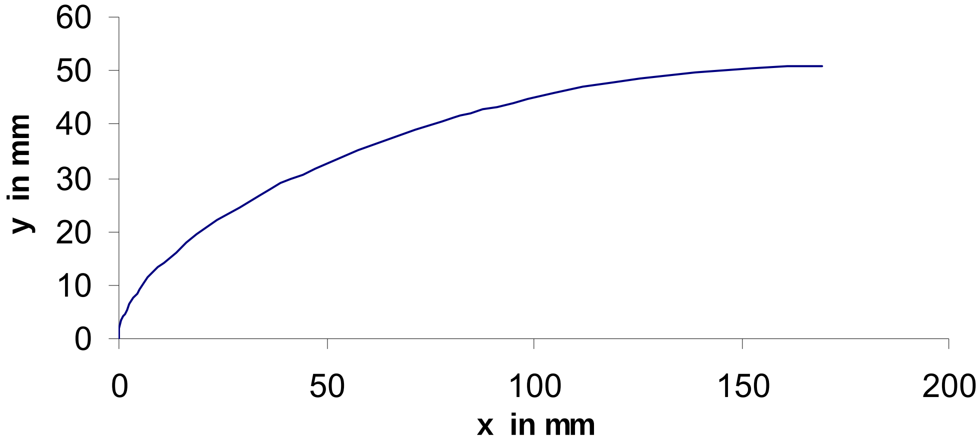

Fig.2. NACA 1 profile for the outer lip

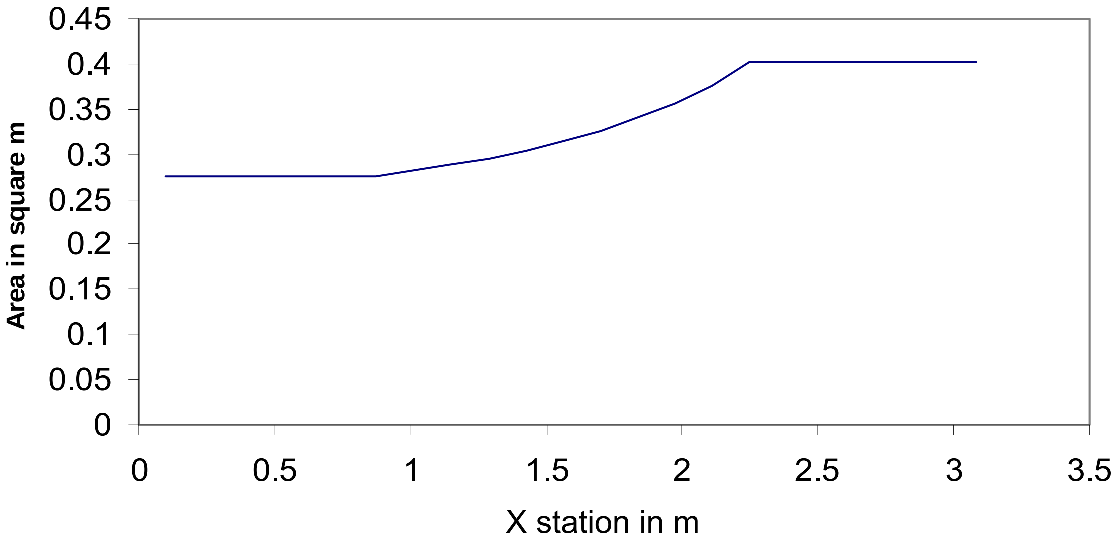

Fig.3. Intake area distribution

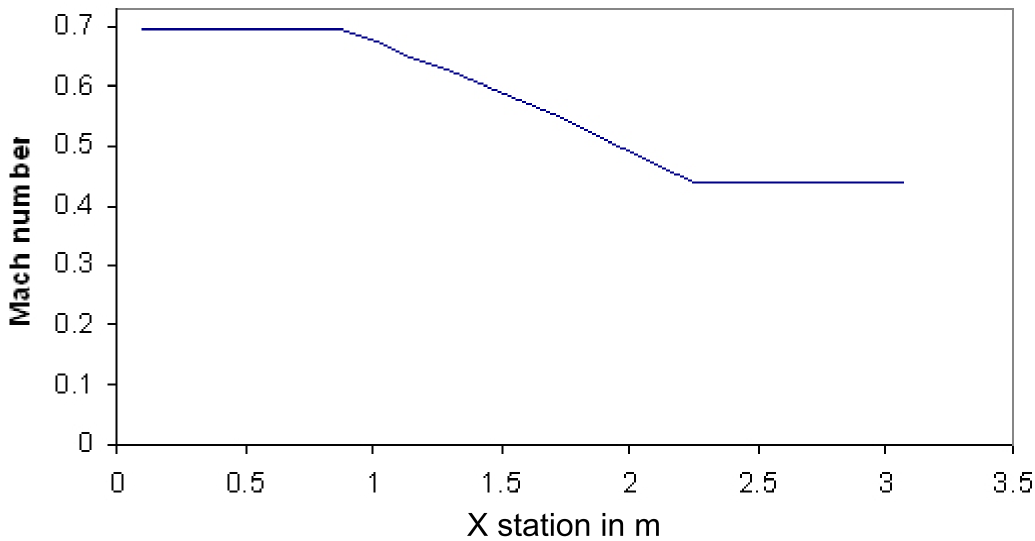

Fig.4. Intake Mach number distribution

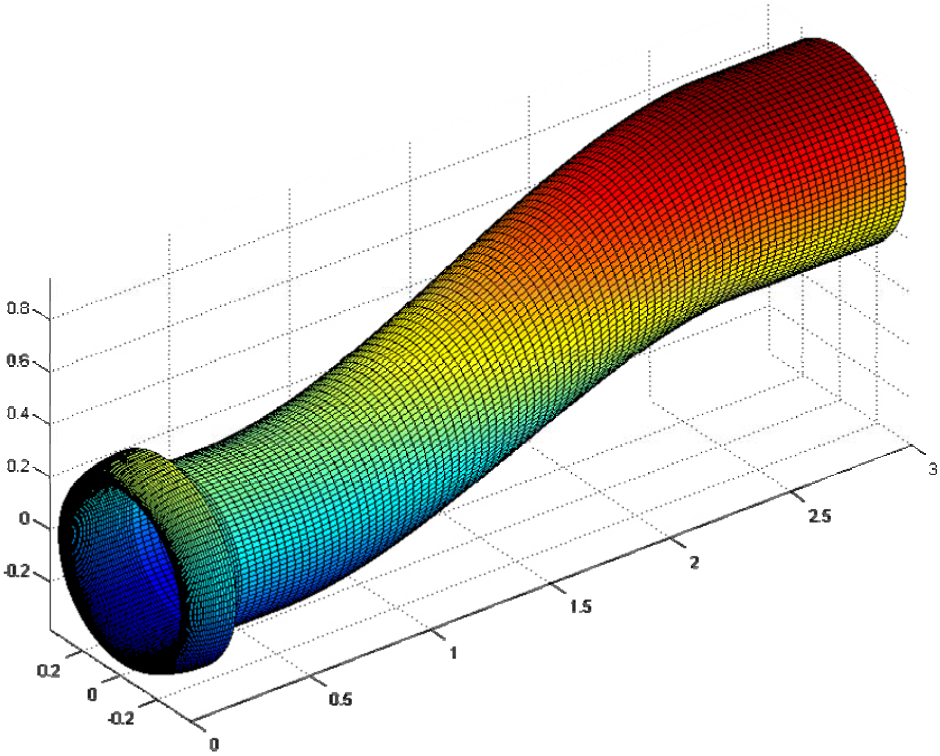

Fig.5. Optimal Intake surface obtained from low fidelity optimization

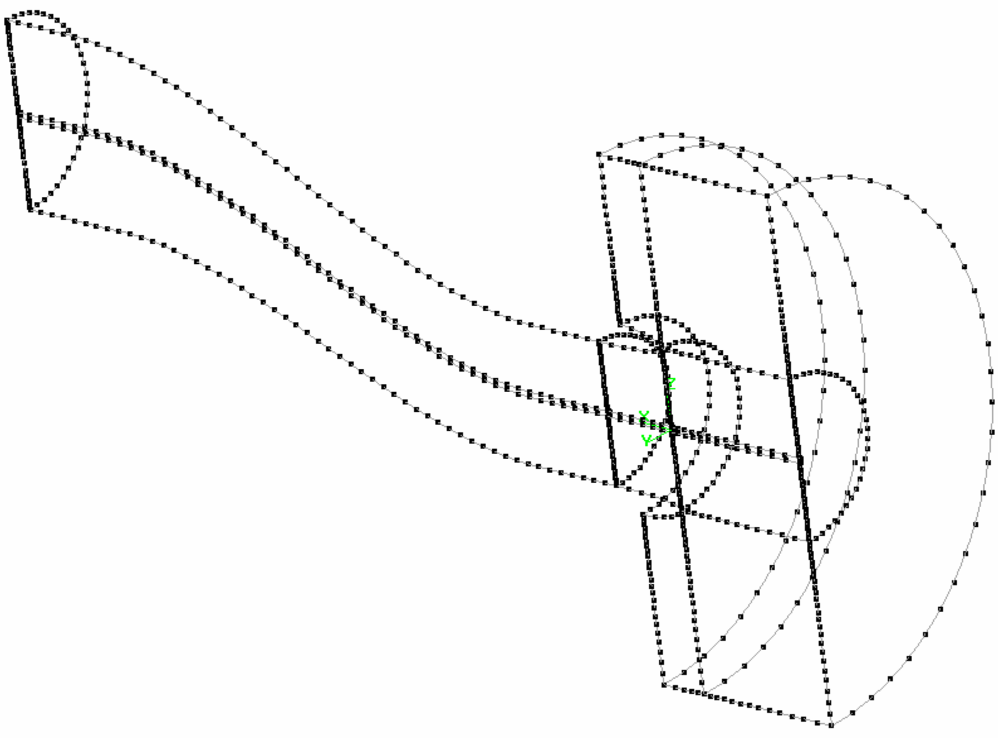

Fig.6. Intake edge grid and clustering

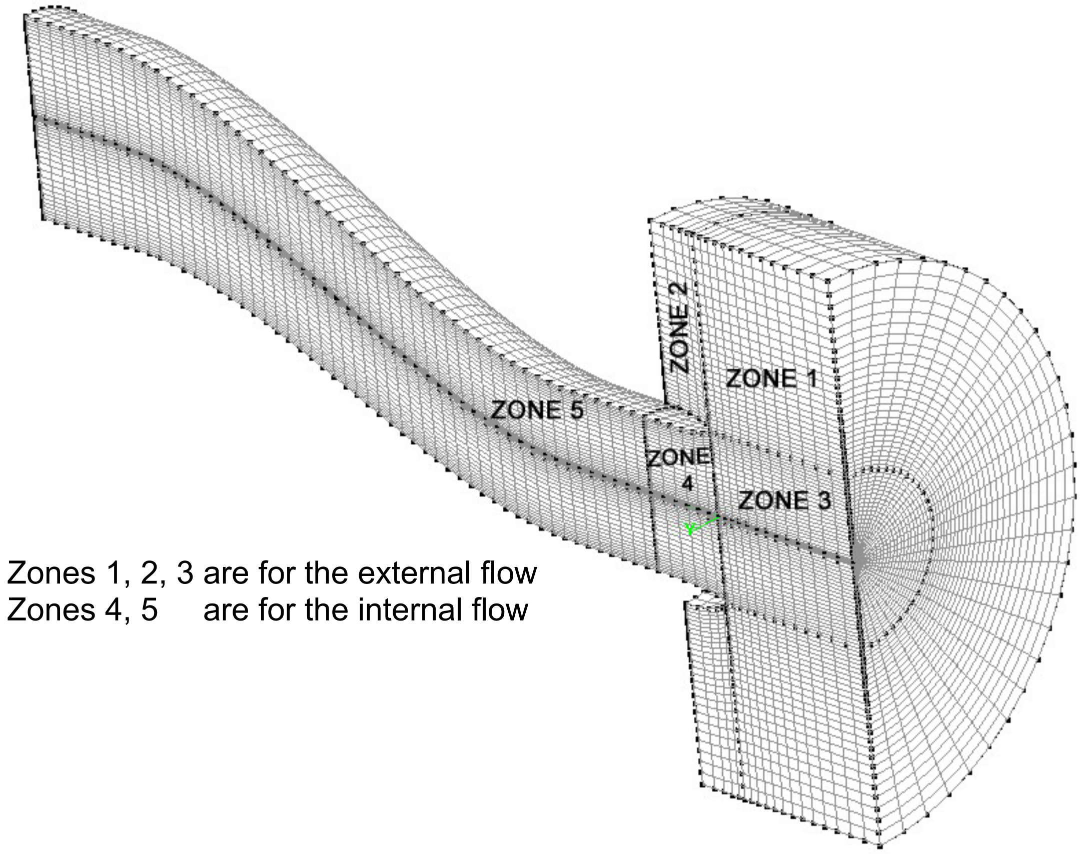

Fig.7. Intake volume grid with the multi zone illustrated

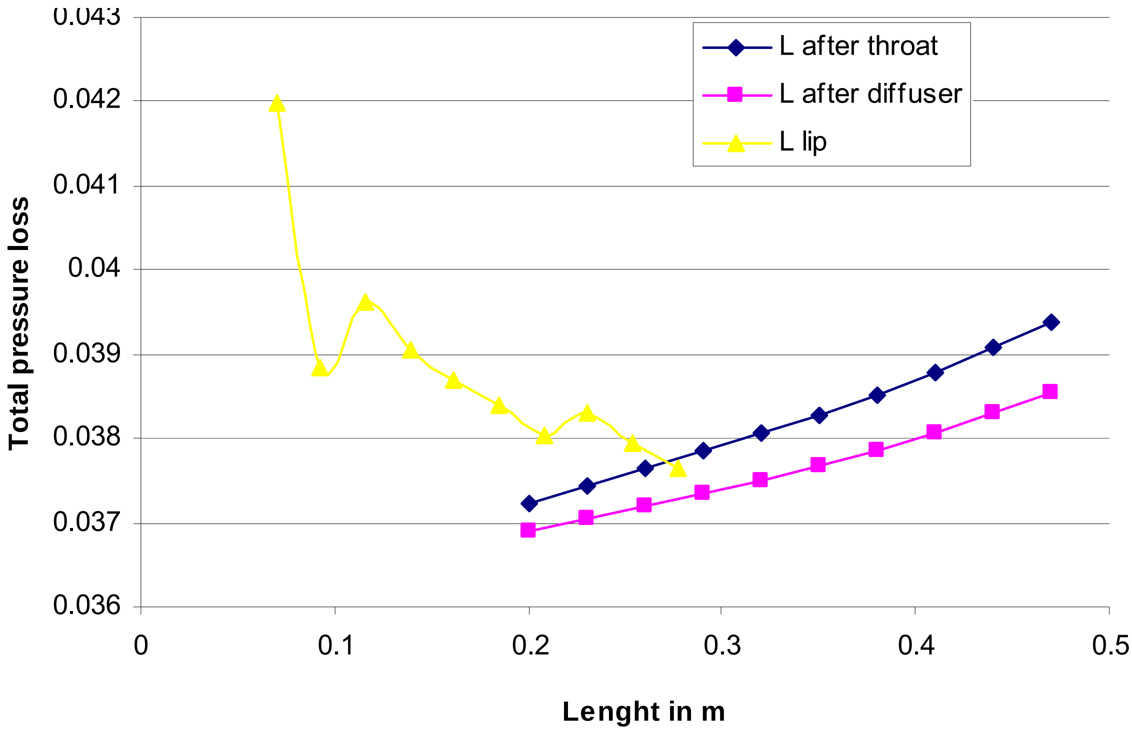

Fig.8. Total pressure losses for lengths variables

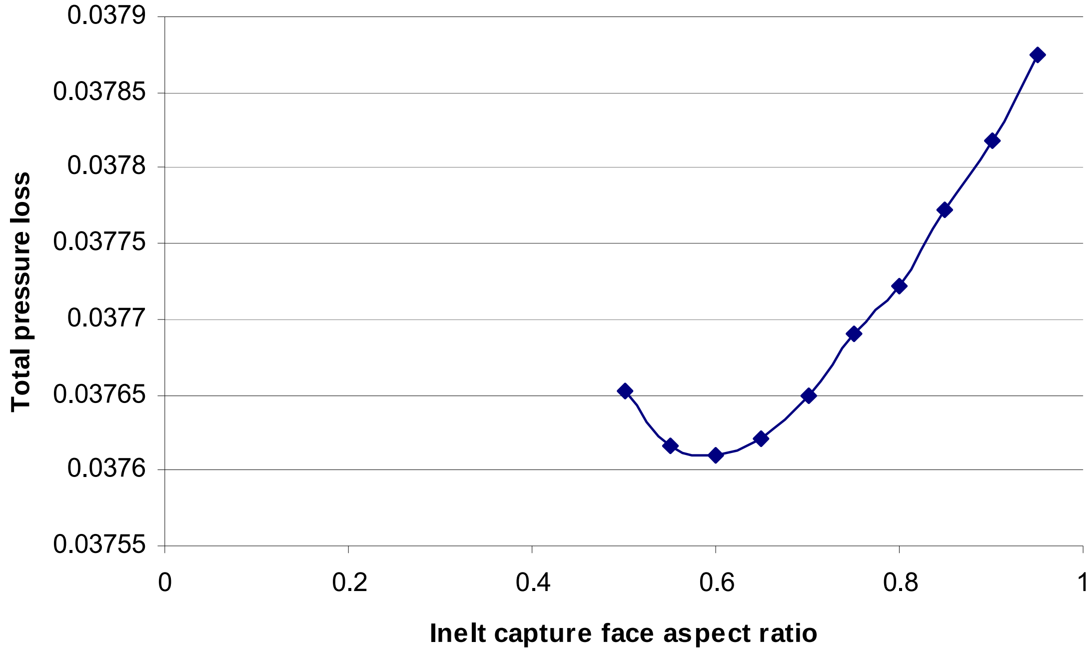

Fig.9. Inlet capture face aspect ratio effect on the total pressure loss

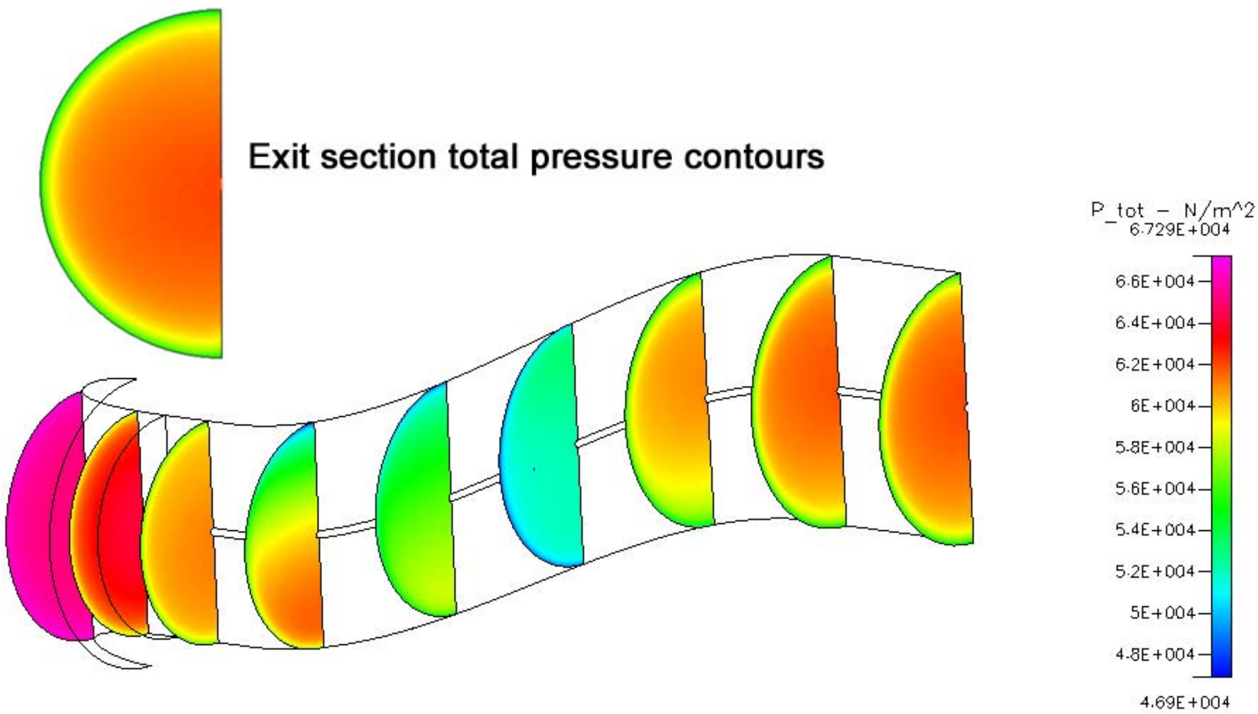

Fig.10.Total pressure sections contours for the optimal intake

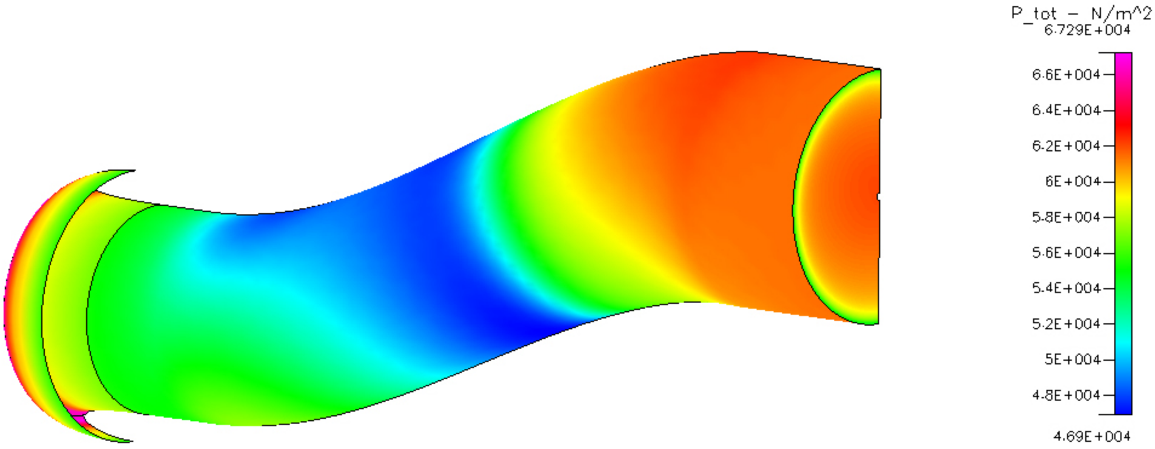

Fig.11.Total pressure contours on the optimal intake surface

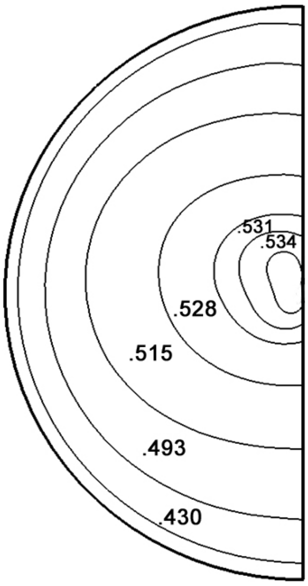

Fig.12. Mach number contours plot for the exit section for the optimal intake

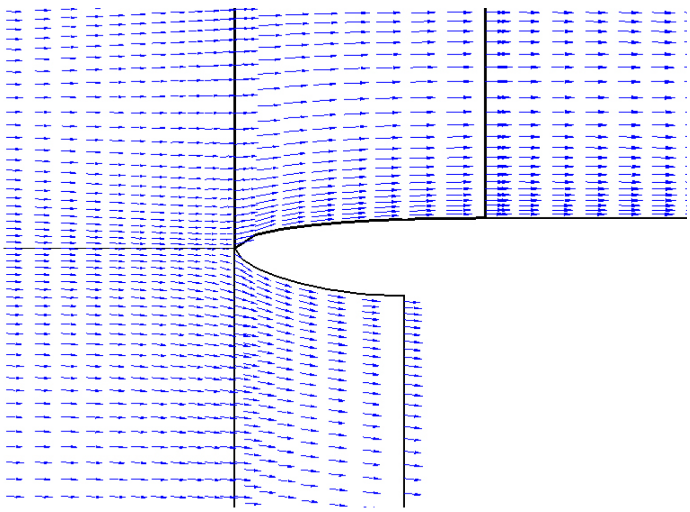

Fig.13. Velocity magnitude and direction vector plot around the lip of the optimal intake

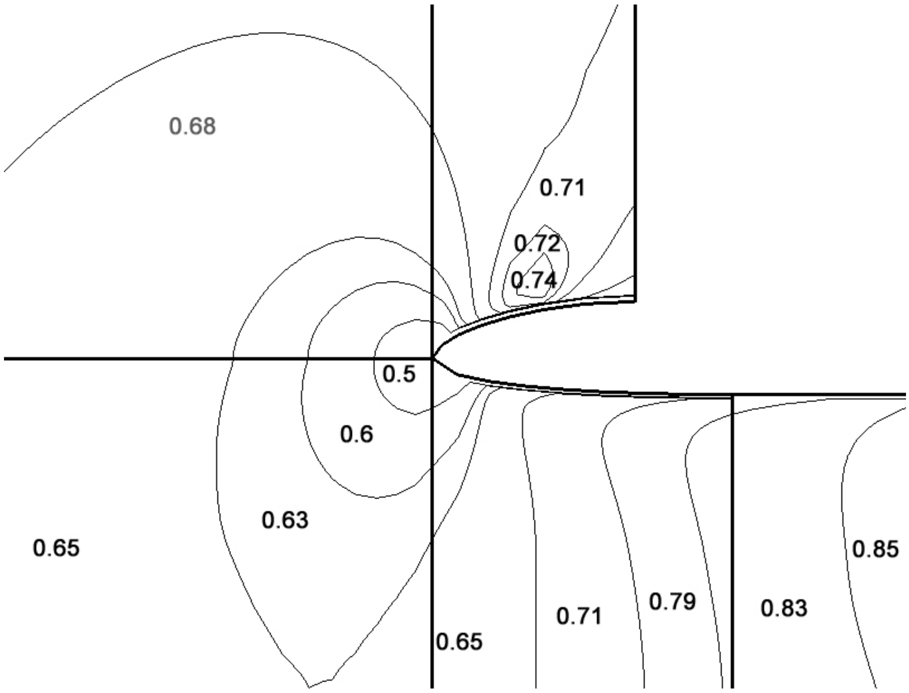

Fig.14 Mach number contours around the lip of the optimal intake

Table1. Low and high fidelity optimization results

Parameters/ Results	Low fidelity Genetic algorithm	High Fidelity Simplex
Lip length in m	0.2784	0.2916
After throat duct length in m	0.2217	0.3784
After diffuser duct length in m	0.4780	0.2996
Capture face type	ellipse	ellipse
Capture face aspect ratio	0.9897	0.8594
Centre line equation	EQ (2)	EQ (3)
Fillet factor	NON "valid for rectangle"	NON "valid for rectangle"
Total pressure loss	1.51%	3.48 %

Table2. Discrete parameters effect on the total pressure loss

Discrete parameter	Total pressure loss
EQ(1)	0.037553
EQ(2)	0.037764
EQ(3)	0.035011
EQ(4)	0.046706
Ellipse capture face	0.037764
Rectangular capture face	0.04334

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