PROPULSION SYSTEM - AIRFRAME INTEGRATION AND OPTIMIZATION OF CIVIL AIRCRAFT- AGILE EU PROJECT

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Abstract

Nacelle shape optimization for Blended Wing Body (BWB) is performed. Optimization procedure is based on numerical calculations of the Reynolds-averaged Navier- Stokes equations. To find the optimum solution surrogate-based Efficient Global Optimization algorithm is used. This whole procedure is considered in the context of the third generation multidisciplinary optimization techniques, developed within AGILE project. During the project, new techniques should be implemented for the novel aircraft configurations, chosen as test cases for application of AGILE technologies. It is shown that the optimization technology meets all requirements and is suitable for using in the AGILE project.

1 Introduction

The AGILE EU Project [1] is dedicated to the development of distributed multidisciplinary optimization methodology. The project is based on the key technologies developed over the last 10 years in the DLR: such as, for example, a common data format CPACS [2] and RCE [3] environment. The main purpose of AGILE project is to reduce by 20% the time of the convergence process in the aircraft optimization and by 40% for the multidisciplinary optimization in a team of various experts by the end of 2018. It will reduce the time of advanced aircraft development and bring them to the market faster. In the framework of the project, the created methodology will be applied to a number of non-standard configurations. As a result, it is expected to obtain results for perspective aircraft. However, the use of non-standard configurations needs in flexibility of the developed methods and possibilities of application for a wide range of aircraft. It significantly increases its value. There were several BWB studies carried out from Liebeck 2004 [4] to recently Vos et al [5] and also subsystem design studies for civil aircraft which will be extended to BWB [6] and uncertainty studies [7]. This is the first time a collaborative multinational heterogeneous teams is analyzing the BWB configuration.

The main objective for TsAGI in the current project is to optimize the external aerodynamics of the power plant. This task is possible within the framework of the project, because the project ideology at each step of the global optimization permits both the disciplinary analysis and the disciplinary optimization. At that, a number of specific requirements are made to the optimization. One of such requirements is the optimization speed, because it is necessary to optimize the external aerodynamics of outer nacelle at each step of global optimization. It is desirable to ensure that the optimization process takes a time equal to one step of time global optimization. The other requirement is the flexibility of the developed methodology, because it is supposed to optimize non-standard configurations with non-traditional arrangement of engines at the subsequent stages of the work.

Thus, the developed methodology should allow to optimize the aerodynamics of a wide range of propulsion systems.

This methodology is developed both in itself and as part of a larger project. It imposes an additional restriction on the optimization process. It should be easily integrated into a global optimization methodology and being its integral part. For that, the methodology should to be well described and understood by all consortium members, it is to have a clear set of input and output parameters coordinated by all consortium members, as well as to use a common data format. To solve the latter problem, CPACS is used as a common format in the project. To facilitate the communication between the partners, the project uses the general environment of RCE development. Propulsion aerodynamic calculations are carried out by using TsAGI in-house solver Electronic Wind Tunnel (EWT) [8].

During the first two ears of the project, the methodology was made and improved to the level of readiness for practical application [9]. In the third year, the technology should be applied to the unconventional configuration. One of the reference aircraft for optimization was chosen BWB. This configuration is very perspective because of possibility to receive very high lift to drag ratio and as a result low fuel consumption. Nevertheless, the nacelle position under the fuselage leads to the huge interference between nacelles and fuselage. It leads to strong shock waves and separation bubbles in nacelle area. As a result, the big drag of this configuration may bring to naught all advantages of BWB configuration. All our efforts have been directed to the supplying appropriate aerodynamic shape of configuration for the receiving best solution during multidisciplinary optimization.

2 Task formulation

2.1 Problem statement

In the project beginning, the Top Level Aircraft Requirements were formulated [6]. The initial shape of airframe also was design (Fig. 1). The requirements for airplane was reformulated to the initial parameter of optimization:

Cruise Mach Number = 0.8;

Operation Altitude = 10668m (35000ft);

Operation weight = 300 000 kg (it means Cy=0.5185 for the BWB with mentioned above parameters and wing area is equal to 900 m^2);

The main advantages of BWB aircraft should be aerodynamic efficiency and low fuel consumption. For satisfying these demands as objective function was chosen effective thrust losses. The minimization of this function lead to the optimal solution in terms of aerodynamic and fuel efficiency.

For this configuration the decisions was made to use three engines over the fuselage. The engines for these task was designed. The engine parameters are listed in Table 2. This is the overpower engine for perspective airplane.

Table 1. Engine parameters for BWB configuration

Engine Overall Length	6.436m
Fan length	1.0046m
Core length	3.89
Fan inlet outer diameter	3.2563
Fan inlet inner diameter	0.9769
Fan bypass exit outer diameter	3.2563
Fan bypass inlet inner diameter	1.65
Core exit outer diameter	1.74
Core exit inner diameter	0.93
Fan bypass exit total pressure	64167.523Pa
Fan inlet total temperature	292.395K
Fan bypass exit mass flow rate	601.6325kg/s
Core exit total pressure	54956.04Pa
Core exit total temperature	715.039K
Core exit mass flow rate	57.945kg/s

For these parameters, the propulsion system was designed. The optimization procedure was divided in two steps. At first step, the isolated nacelle was designed and optimized for cruise regimes. This step is listed in paragraph 3. At second step the nacelles positions over airframe were optimized. This step is listed in paragraph 4. Such division for steps permits to reduce the calculation resources for optimization of overall aircraft with the good results in terms of optimal solution.

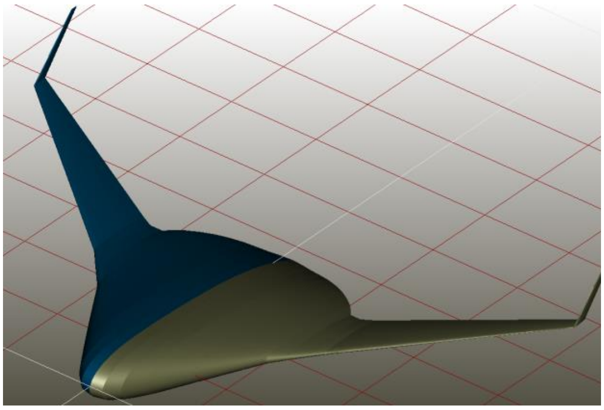

Fig. 1. Reference airframe for engine design

2.2 Solver

All the calculations were performed based on the full 3D non-stationary Reynolds equation system closed by Spalart-Allmaras turbulence model. Solver EWT-TsAGI is based on the finite-volume numerical method that has the second approximation order in all variables and includes the monotonic modified Godunov scheme for approximation of convective fluxes, the central-difference approximation of diffusive fluxes and two-layer point-implicit approximation of source terms. Detailed description of this method is given in [8]. The calculations are performed on multiblock structured grid with hexahedral cells. The method permits to use irregular joining the blocks with the discontinuity of grid lines at the boundaries of blocks. To speed up calculations of steady flows, the implicit scheme is used. Bellow, for simplicity and brevity, the scheme will be formulated for a scalar model equation that contains convective fluxes only.

$$\frac{\partial u}{\partial t} + \frac{\partial F(u)}{\partial x} = 0 \qquad (1)$$

In this scheme, both the approximation of the physical time derivative and the implicit part of spatial operator has only the first accuracy order. Jacoby matrices are calculated at the known time layer. Only the explicit part of spatial operator is approximated using the 2nd accuracy order scheme. The system of algebraic linear equations, which is based on (1), is solved approximately by 6 iterations of Gauss–Seidel method for block diagonal matrices. If the stationary solution exists, the convergence to this stationary solution is usually better and essentially quicker than the convergence for such schemes as explicit scheme with local–time stepping or with multigrid acceleration.

2.3 Mesh Recreation

During optimization with using CFD methods, it is needed to determine characteristics of a huge number of investigated object geometry variants while carrying out optimizing processes. Using CFD methods with meshes it is needed to build a mathematical model for an each variant. An automatic computational mesh creation must be realized for the effective optimization algorithm working. Automatic creation methods are good developed for unstructured meshes. But created mesh is not optimal because absence of evolved directions and cell form restrictions. Structured computational meshes possess higher total quality. Structured computational meshes disadvantage is there creation complexity. Automatic creation methods for structured mesh are bad developed and work only for rather simply geometrical objects.

In the present work automatic algorithm for structured computational mesh rebuilding is developed. The algorithm is consists of several procedures:

- a base geometry creation of an object and saving it in the IGES/STEP format;
- a structured computational meh creation for the base geometry in the semiautomatic regime;
- writing changed geometry in the IGES/STEP format;
- a surface grid for the changed geometry is created using two geometrical files in the IGES/STEP format and base geometry computational mesh;
- 3d mesh for the changed geometry is created using its surface grid and 3d mesh for base geometry.

All operations are made in program Grid_Creator [11] developed in TsAGI (Russia). Free library “cgnslib” version 3.1.3 is used in the program Grid_Creator for operation with CGNS format. In addition Grid Creator has a number of additional functions: usage of additional possibility of EWT-TsAGI [12] solvers (families, turbulence model parameters and etc.), setting of irregular flows on the computational region boundary, cluster load optimization.

Let's consider surface and three-dimensional computational meshes rebuilding. Base grid could be uploaded from internal format or from CGNS format (Fig. 2). Modified surface grid is created using base and modified geometries in IGES/STEP format and base grid. Operations with geometry (reading, saving, projection on surface and etc.) are processed using free software OpenCASCADE 6.9.0 [13]. It is dynamical library which include wide range of functions needed for operations with geometry. Base computational mesh is linked to base geometry: vertexes of mesh blocks to geometry points. Linking is made by comparison of vertex and point coordinates with some accuracy.

Blocks vertexes are moved in accordance with linked points changing while surface grid modification with modified geometry. Coordinates of non-linked blocks vertexes are changed using 4 nearest points using revers distance interpolation. Block edges are rebuilt by vertex deformation using line interpolation. If a full base edge was on some base curve and new edge vertexes are on a new curve, that the new edge is projected on the curve. All others edges are projected for each node. If a node was on a base curve, that new node is projected on new nearest curve.

Field of coordinates changing for all inner nodes is created by blocks edge moving. Then all surface nodes are projected on nearest geometry surface. It is possible to project nodes on geometry by families. That is base node family is detected and a new node is projected on a surface of the same family.

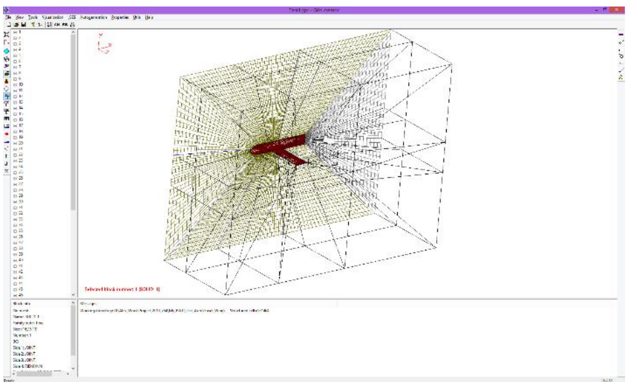

Fig. 2. Blocking structure in Grid_Creator program

New 3D computational mesh creation for the modified geometry is required:

- Base 3D mesh;
- Base surface grid;
- Modified surface grid.

Parameter for procedure is a number of corrected layers of mesh

- 0 — for the mesh without boundary layer. Only block layer placed near surface is changed.
- 1 — layer of boundary blocks is moved equidistant by surface, and next layer is rebuilt linear. Boundary blocks is fully moved but next layer is deformed;
- ≥2 — layers after boundary is moved on smaller and smaller distance.

After blocks side modification inner mesh must be rebuilder for all blocks. The checking procedure is running automatically after mesh rebuilding. Checking consist of calculations of cells volume, cell twistedness and sides twistedness.

2.4 Optimization Algorithm

During the optimization, the value of effective thrust losses (2) for isolated nacelle at the cruise regime has been used as an objective function.

$$dP_{eff} = P_{id} - P_{eff}, \qquad (2)$$

where

P_{id} — the ideal engine trust;

$P_{eff} = P - F_x$ — the effective engine trust (thrust-minus-drag);

P_{id} — the engine thrust determined with the use of the internal parameters;

F_x — projection of the total force of external drag on the engine axis;

As an optimizer code, SEGOMOE, developed by ONERA [14] is used. SEGOMOE is very efficient for the tasks with expensive problem, in terms of computing resources, with moderate noise pollution (depending on the used calculation method of and the grid detalization), and non-zero probability of finding local extremes. It means that it is possibly necessary to use global nongradient-based optimization methods with the purpose to reduce the noise influence and try not to get into local extremum.

3 Isolated Nacelle Optimization

3.1 Parametric Isolated Nacelle Model

Based on the authors experience, which has been obtained in the optimization of nacelle turbofan engine with high bypass ratio [15], and based on the results of calculations performed in the preliminary design stage, it has concluded that there is weak interference between the nozzle and the inlet. Therefore, the initial problem of designing the aerodynamic contours of nacelle has been divided into two independent problems about optimization of nozzle and inlet shapes.

Nacelle geometry has been divided in two parts at mid-section. At that, mid-section diameter and position are nacelle parameters. For this reason, the nozzle has been designed at the first stage. At the second stage, the inlet has been designed for mid-section diameter and position chosen at the first stage.

The method of nacelle nozzle geometry parameterization adopted in this study is illustrated in Fig. 3.

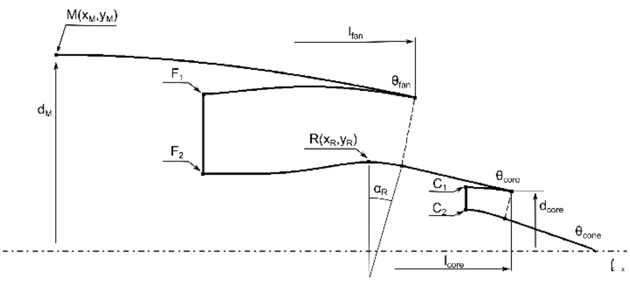

Fig. 3. Nozzle scheme

The point M in Fig. 3 (mid-section point) corresponds to two parameters: nacelle mid-section position and diameter. The points F_1 and F_2 are fixed, they define the entrance into the fan nozzle. The points C_1 and C_2 define the entrance into core nozzle and are fixed too. The rest of the nozzle geometry is varied with the use of 11 controlling geometrical parameters. The areas of exit sections of both nozzle jets are chosen so as to provide necessary costs for take-off and cruise regimes.

The controlling geometrical parameters are listed in Table 2.

Table 2. Nozzle controlling geometrical parameters

x_M	mid-section position of nacelle
d_M	mid-section diameter of nacelle
θ_{fan}	convergence angle of fan nozzle cowling relatively the nozzle symmetry axis
l_{fan}	position of fan nozzle cowling edge
x_R	position of maximal height point of gas generator fairing
y_R	value of maximal height of gas generator fairing
α_R	inclination angle of bypass jet critical section
θ_{core}	convergence angle of gas generator fairing cone
d_{core}	diameter of gas generator fairing edge
l_{core}	position of gas generator fairing edge
θ_{cone}	convergence angle of central body of core nozzle

Figure 4 presents an inlet scheme used in the current paper. The geometry is given with the use of 7 controlling geometrical parameters: 6 parameters define axisymmetric inlet and 1 parameter (angle of setting) is used in designing 3D inlet.

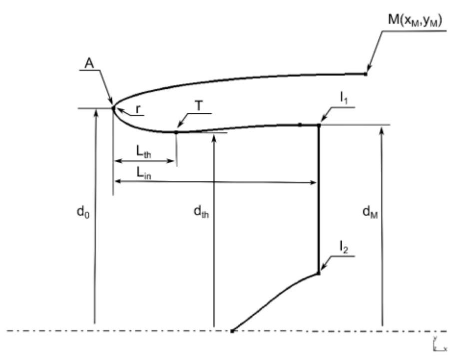

Fig. 4. Inlet scheme

The point M in Figure is mid-section point with coordinates x_M and y_M that are defined by the nozzle geometry. The geometry of the inlet cowling outer surface (curve AM) is given by Bezier spline plotted on 4 points and is defined by curvature radius of nose r. The geometry of in inlet cowling inner surface (curve

AT) is also given by Bezier spline plotted on 4 points. Curves *AM* and *AT* are given to provide necessity of the first and the second derivatives at the point *A*. The inlet throat d_{th} is chosen with taking into account the restrictions of throat loading; diameter d_0 at the leading edge is defined through the throat diameter and lip thickness coefficient. The position of engine entrance (points I_1 and I_2) and engine shaft cowling are fixed.

The controlling geometrical parameters of the inlet are listed in Table 3.

Table 3. Inlet controlling geometrical parameters

L_{in}	inlet length
d_{th}	throat diameter
L_{th}	distance between the leading edge and inlet throat
K	lip thickness coefficient of the inlet: $K = \frac{d_0}{d_{th}} - 1$
r	the curvature radius of the inlet lip
B_1	Bezier spline parameter defining the inner surface geometry of the inlet
φ	inclination angle of bypass jet critical section

After the designing a shape of the axisymmetric inlet, setting of the inlet takes place: the inlet axis rotates around the *OZ* axis at an angle φ with respect to the engine axis.

3.3 Procedure and Results

Figure 5 shows the convergence of effective thrust losses received by SEGOMOE. For this task it is used 30 DOE points for 18 parameters and 2 constrains. For constrains the ratios throw each counters were used. After 90 points, SEGOMOE found the optimal solution with satisfying of constraints. The further calculations (Figure 5) showed that the founded solution was optimal. It is very good results for optimizer with this kind of task.

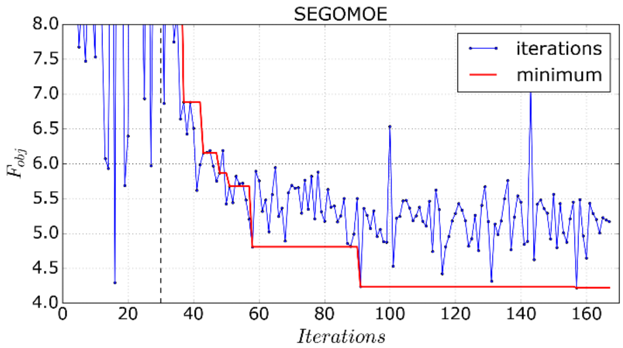

Fig. 5. Convergence of effective thrust losses by SEGOMOE

4 Engine/Airframe Integration

The position optimization was proceeded like the isolated nacelle optimization. In this case, the design parameters were:

x and z coordinates of central nacelle;

x, y and z coordinates of side nacelle;

angle of attack of nacelles. The angle was the same for all nacelles;

sweep angle for side nacelle;

aircraft angle of attack. This perimeters is necessary for supplying of constrain.

As a constrain was used the lift force for satisfying (equivalent of Cy=0.5185) of Top Level Aircraft Requirements for Operation Weight.

After finishing optimization procedure the optimal parameters showed in Table 4 were received.

Table 4. Optimal parameters

Central_Engine_cg_x	34.0741
Central_Engine_cg_z	4.0741
Central_Engine_alfa	5.37
Side_Engine_cg_x	33.1926
Side_Engine_cg_y	5.1926
Side_Engine_cg_z	4.0741
Side_Engine_alfa	5.37
Side_Engine_beta	1
AoA	1.75

The received lift coefficient for overall configuration was Cy=0.5185. This means satisfying of requirements. The final configuration is presented at Figure 6.

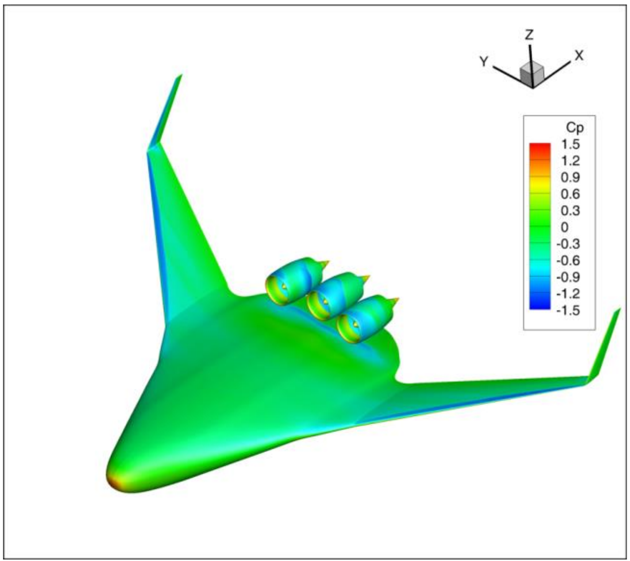

Fig. 6. Pressure coefficient distribution over BWB aircraft with three optimal engines

The received data analyze permits to say about huge negative interference between wing and fuselage. During optimization all parameters trying to increase the distance between nacelles and nacelles and fuselage to reduce the interference. But the constrain and range of variety force them to be together. If we will analyze the thrust of different engines we can find the thrust of central engine equal of Pc= 75244.52 and side engine Ps=77721.41. This is showed the bigger efficiency of side engines because of low interference. This fact point out the conclusion about negative interference.

5 Conclusions

The task aerodynamic design of propulsion system were successfully made for BWB configuration. The airplane with three optimal engines satisfying the Top Level Aircraft Requirements. This configuration is appropriate for further investigation in this area and possible be used for multidisciplinary optimization of overall aircraft. During further investigation the huge attention should be paid to the aerodynamic interference between airframe and fuselage.

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