AERODYNAMIC OPTIMIZATION OF AIRPLANE PROPULSION SYSTEM WITHIN THE FRAMEWORK OF AGILE PROJECT

K.S. Anisimov, A.A. Savelyev
Central Aerohydrodynamic Institute (TsAGI)

Keywords: *optimization, CFD, inlet, engine nacelle, power plant*

Abstract

Nacelle shape optimization for classical configuration airplane 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

Now, in the framework of the program "Horizon 2020", the methodology of distributed multidisciplinary optimization is developed. The project devoted to this topic and supported by the European Union is named as AGILE (Multidisciplinary optimization of the 3rd generation in the framework of innovation cooperation of various specialist groups). The current project is coordinated by the Institute of Air Transportation Systems of German Aerospace Center DLR. 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 [1] and RCE [2] 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.

20 partners from Europe, Canada and Russia take part in AGILE project consortium. The number of participants and the variety of the team research directions underlines the complexity of multi-disciplinary optimization of modern aircraft. Among the consortium members, there are specialists in multi-disciplinary optimization and disciplinary optimization in various fields of aviation science as well as industry representatives. The main role of industry representatives is to formulate high-level requirements and to estimate the quality of the obtained result from the practical point of view. The problem for the specialists in the multidisciplinary optimization is to formulate the problem and to coordinate the relations between specialists in disciplinary analysis. The specialties of the experts in disciplinary analysis cover all areas of aircraft research at the preliminary design stage. This project ideology allows experts to carry out both analysis of the selected disciplines and disciplinary optimization of the selected part at each step of global optimization.

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) [3].

2 Problem formulation

As it has been described above, the project needs in a methodology for optimizing the external aerodynamics of the outer power plant. This methodology is to be easily integrated into the aircraft multidisciplinary optimization. TsAGI has large experience in the aerodynamic design of both an isolated nacelle [4], [5], and as a part of an airframe [6]. The main research tool is a EWT-TsAGI code. TsAGI has performed design using EWT [7]. In previous works, nacelles designing has been performed without taking into account the other disciplines; only constructive limitations has been taken into account. The nacelle parameterization has been taken from the previous experience.

To create such optimization, it has been decided to divide all variable parameters to external and internal these. The external parameters are the only ones that are used by all consortium members and influence on many disciplines, not only on the external aerodynamics of the power plant. The internal parameters are those that are used to optimize the external aerodynamics of the power plant only and does not require other consortium participants.

Among the external parameters, following were selected: the coordinates of the power plant center, the diameter and length of the engine, engine thrust, and the bypass ratio of the power plant. These parameters essentially influence on the most important disciplines that are studied by other consortium members, such as the aircraft balancing, engine weight and type, the aerodynamics of the aircraft as a whole and others. These parameters are widely used in the exchange between the partners, so they are all written in a common file in CPACS format.

The internal variables that allow to parameterize the aerodynamic contours of the power plant are considered only. Thus, in this paper, the problem to optimize the external aerodynamics of the power unit is reduced to optimization, when the internal variables are varied and the external variables are assumed to be given and used as the input parameters. To provide the flexibility of methodology and its applicability for a wide range of aircraft, it is necessary to ensure the work of optimization methodology on the basis of internal variables in a wide range of external variables.

3 Grid creation

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 [8] 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 [7] 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. 1). 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 [9]. 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.

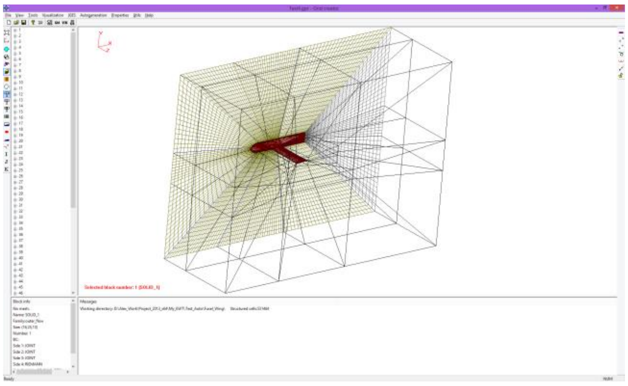

Fig. 1. Blocking structure in Grid_Creator program

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.

5 Nacelle Optimization

5.1 Parametric Nacelle Model

Based on the authors experience, which has been obtained in the optimization of nacelle turbofan engine with high bypass ratio, 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. 2.

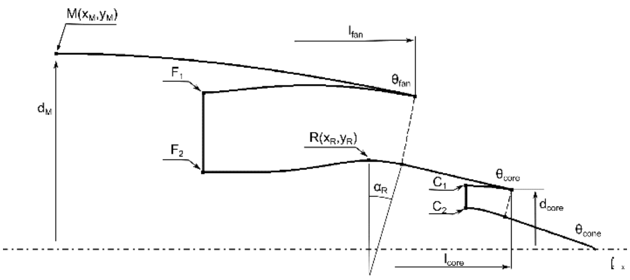

Fig. 2. Nozzle scheme

The point M in Fig. 2 (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 1.

Table 1. 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 3 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.

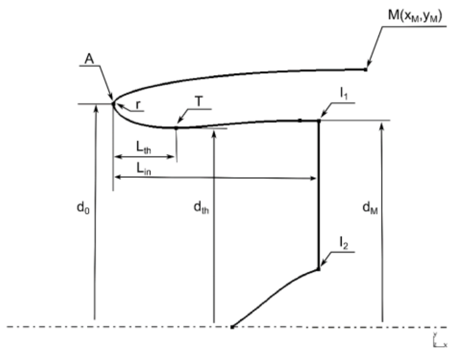

Fig. 3. Inlet scheme

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 2.

Table 2. 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.

5.2 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 [10]. 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.

5.2 Optimization Algorithm

As an optimizer code, free cross-platform software with open source code Dakota, developed by Sandia National Laboratories [11] is used. The software package Dakota (Design Analysis Kit for Optimization and Terascale Applications) is a series of libraries that allow to perform factor analysis and design of experiments, to solve optimization problems, to calibrate and evaluate the sensitivity and reliability of the systems. Interaction with external codes is organized by file sharing.

To solve optimization problems, Dakota provides a series of methods that can be divided into 3 types: local gradient-based, local nongradient-based and global nongradient-based methods. In addition, one can organize hybrid strategy, consistently applying several methods in the hope to use advantages of each.

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

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

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;

Effective thrust calculation of the turbofan engine can be considered as 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. In this paper, EGO (Efficient Global Optimization) algorithm is used [12]. It is a global optimization algorithm, which uses a surrogate model constructed by kriging method [13].

5.3 Results

The process of optimizing the geometry of the nacelle by EGO algorithm is shown on Fig. 4. To find the 18 optimal geometric parameters algorithm needed 390 iterations. The figure clearly shows two steps of the algorithm: the construction of initial surrogate model by design of experiments method and the further refinement of the model in the local areas of interest.

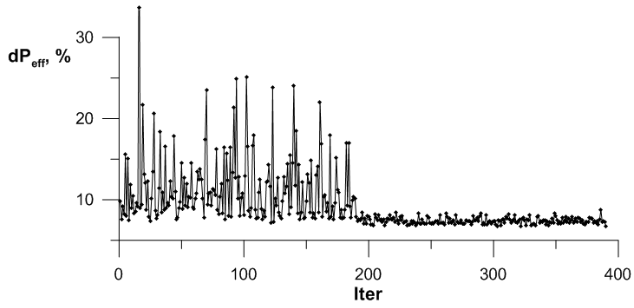

Fig. 4. Changing the values of the objective function in the optimization process

Analysis of optimal parameters showed that the behavior of the geometrical parameters describing the inlet and the nozzle are essentially different. Optima of the majority of nozzle parameters are located within the variation range and do not come close to the borders.

The situation is reverse with the intake. In this case, the analysis of the optimal parameters has shown that a number of restrictions are active: optimal values of the throat diameter, the lip thickness coefficient and the curvature radius of the inlet nose belong to the down border of variation, while the optimum value of the distance from the leading edge to the inlet throat tends to a maximum. Changing the boundaries of these parameters variation will result in a violation of TsAGI’s recommendations for the inlet design. Reducing the throat diameter will increase its loading; reducing the lip thickness coefficient and the nose curvature radius can lead to flow separation at the inlet entrance at the takeoff regime with crosswind and at the cruise regime in the case of high incidence angles; throat shift toward the engine entrance will increase the diffuser expansion angle and, hence, will increase the probability of separation in the inlet duct. There is an unexpected fact that the optimal inlet length does not tend to the minimum possible value, and is roughly in the middle of the variation interval.

Figure 5 presents a flow around designed nacelle at cruise regime with Mach number $M_\infty = 0.78$. Lines in Figures demonstrate isolines of Mach number $M = 1.0$. As it is obvious in Figures, there are no flow separation and strong shocks. The effective thrust losses at cruise regime are $dP_{eff} = 6.7$ %.

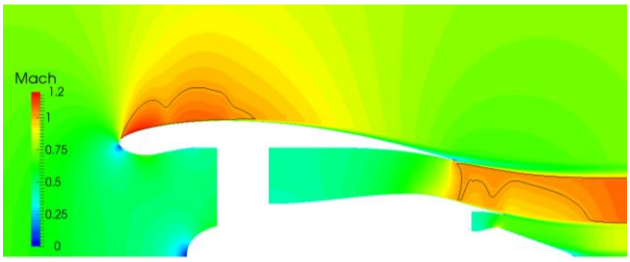

Fig. 5. Nacelle optimal geometry, Mach number field at cruise regime $M_\infty = 0.78$

A flowfield for takeoff regime ($M_\infty = 0$) is given in Figure 6. As it can be seen from the figure, there are no flow separation and supersonic flow zones in the flow. As a result, the total pressure recovery ratio at the entrance to the engine is $\nu = 0.996$, which corresponds to the recommended standard.

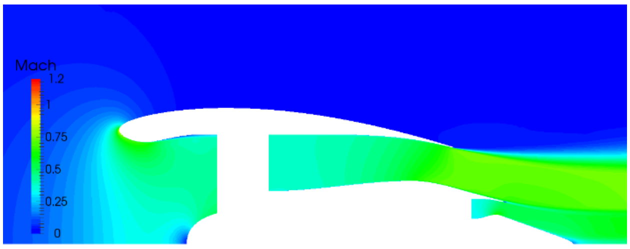

Fig. 6. Nacelle optimal geometry, Mach number field at takeoff regime $M_\infty = 0$

6 Conclusions

During the current work, it has been possible to create a methodology to optimize the external aerodynamics of the aircraft power plant. This methodology meets to all the requirements and is suitable for using in the AGILE project.

7 Acknowledgments

The research presented in this paper has been performed in the framework of the AGILE project (Aircraft 3rd Generation MDO for Innovative Collaboration of Heterogeneous Teams of Experts) and has received funding from the European Union Horizon 2020 Programme (H2020-MG-2014-2015) under grant agreement n◦ 636202. The authors are grateful to the partners of the AGILE consortium for their contribution and feedback.

The Ministry of Education and Science of the Russian Federation financially support the Russian part. All mentioned in this article studies were carried out in the framework agreement №14.628.21.0004 (Project unique identifier RFMEFI62815X0004).

References

[1] B. Nagel, D. Böhnke, V. Gollnick, P. Schmollgruber, A. Rizzi, G. La Rocca, J.J. Alonso, Communication in Aircraft Design: Can we establish a Common Language?, 28th International Congress of the Aeronautical Sciences, Brisbane, Australia, 2012.

[2] Seider D., Fischer P.M., Litz M., Schreiber a., Gerndt a. Open source software framework for applications in aeronautics and space // 2012 IEEE Aerospace Conference. 2012. pp. 1–11.

[3] Bosnyakov S., Kursakov I., Lysenkov A., Matyash S., Mikhailov S., Vlasenko V., Quest J. Computational tools for supporting the testing of civil aircraft configurations in wind tunnels // Progress in Aerospace Sciences. 2008. Vol. 44. pp. 67–120.

[4] Savelyev A.A., Mikhaylov S.V., Zlenko N.A. Aerodynamic Inlet Design for Civil Aircraft Nacelle // Proceedings of the ICAS Congress. St. Peterburg, Russia, 2014.

[5] Scientific notes of 2015.

[6] Zlenko, Kursakov, Scientific notes.

[7] Neyland, V. Ya., Bosnyakov, S. M., Glazkov, S. A., Ivanov, A. I., Matyash, S. V., Mikhailov, S. V., and Vlasenko, V. V., “Conception of electronic wind tunnel and first results of its implementation,” Progress in Aerospace Sciences, Vol. 37, No. 2, 2001, pp. 121-145.

[8] Certificate of official registration of software program № 2007614396 (Russian Federation). Program for structured mesh creation of 3D objects with deferent types of input data (Grid_Creator), 2007.

[9] http://www.opencascade.org

[10] Bosnyakov S., Kursakov I., Lysenkov A., Matyash S., Mikhailov S., Vlasenko V., Quest J. Computational Tools for Supporting the Testing of Civil Aircraft Configurations in Wind Tunnels. Progr. Aerospace Sci. 2008, Vol. 44, No. 2, pp. 67-120.

[11] Adams B.M., Ebeida M.S., Eldred M.S., Jakeman J.D., Swiler L.P., Stephens J.A., Vigil D.M., Wildey T.M., Bohnhoff W.J., Dalbey K.R., et al. Dakota, A Multilevel Parallel Object-Oriented Framework for Design Optimization, Parameter Estimation, Uncertainty Quantification, and Sensitivity Analysis: Version 6.1 User’s Manual // Sandia Technical Report. 2014. No. SAND2014-4633.

[12] Jones D.R., Schonlau M., Welch W.J. Efficient Global Optimization of Expensive Black-Box Functions // Journal of Global Optimization. 1998. Vol. 13. pp. 455–492.

[13] Cressie N. Statistics of Spatial Data. New York: John Wiley and Sons, 1991.

Copyright Statement