

# AERODYNAMIC INLET DESIGN FOR CIVIL AIRCRAFT NACELLE

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## Abstract

*An algorithm for optimal aerodynamic design of the inlet of civil aircraft engine is considered. The algorithm is based on numerical calculations of RANS equations. Methods for conventional optimization of multiple-factor functions permit to design the appearance of efficient inlet, from the viewpoint of aerodynamics, with a number of aerodynamic and design limitations. To illustrate possibilities of proposed methodology, results of optimizing the shape of inlet of isolated engine nacelle for high-bypass turbofan are presented. This engine is intended for mid-range passenger aircraft.*

## 1 Introduction

The level of aerodynamic efficiency of engine nacelle for high-bypass turbofan (HBT) is defined by a number of geometrical parameters (>25). At that the character and degree of different parameter influence on aerodynamic characteristics of engine nacelle (EN) can be essentially various. Changing some parameters may cause, for example, flow separation, while the effect of varying others may be comparable to the scatter of model thrust characteristics measurement results in different wind tunnels. It is also obvious that the geometrical parameters of EN elements can't be varied independently. For example, change of inlet lip thickness, in the case of the same throat position, inevitably results in change of inlet diffuser entering angle and modification of outer contour nozzle cowling length, in the case of the same total length of engine, changes the length of gas generator and, correspondingly, the angle of its contraction. Therefore, the

aerodynamic design of this type of EN is an extremely complex task, requiring the selection of optimal geometrical parameters both the inlet and nozzle.

An algorithm for optimal aerodynamic design of the HBT nozzle is set forth in [1]. This algorithm allows us to find a solution under conditions when the quality of the designed product evaluated according to several competing criteria (multicriterion optimization). Generalization of the approach to the case of real turbofan nozzle with structural constraints described in [2]. The current paper provides a further development of approaches considered in [1] and [2] to optimization of the power plant elements: it proposes an algorithm for choosing optimal shape of HBT inlet on basis of numerical calculation results of viscous gas flow around cruise power plant. Inlet design in current paper is considered as a step of EN aerodynamic design as a whole.

The problem of optimal aerodynamic design is examined in a strict formulation with obligatory taking into account a large number of both design limitations, which are characteristic for considered type of engine, and aerodynamic limitations due to necessity to provide stable work of power plant and flow without separation around EN for whole range of working conditions. The optimal values of control geometrical parameters are mainly determined during the search of conditional extremum for multiple-factor objective function. The proposed algorithm for optimal aerodynamic design of the inlet has following principal stages:

- parameterization of inlet mathematical model and choice of decisive criterion;

- determination of feasible region of control geometrical parameters with taking into account the design and aerodynamic limitations;
- choice of numerical method for determination of objective function values;
- automation of inlet element shape variation and adaptation of calculation grid to given geometry variant;
- searching the conditional extremum of objective function in the space of control parameters.

Following perspective problems arising due to necessity of attaching the designed EN to a concrete aircraft type remain beyond the current paper: optimization of EN space orientation and minimization of negative effects of interference with airframe.

Workability and efficiency of proposed algorithm for optimal aerodynamic design is shown in terms of optimization of HBT inlet, which is intended for mid-range passenger aircraft.

## 2 Problem Formulation

### 2.1 Flow Peculiarities

A typical pattern of flow around isolated engine nacelle at cruising flight regime with Mach number  $M_\infty = 0.8$  on basis of numerical flow simulation using Navier-Stokes equations is shown in Fig. 1. This Figure, in addition to Mach number field, demonstrates streamlines and supersonic zones restricted by isolines that correspond to Mach number  $M = 1$ .

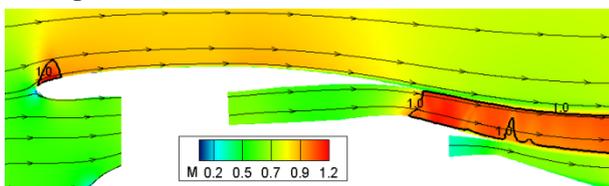


Fig. 1. Mach number field and streamlines corresponded to cruising flight regime ( $M_\infty = 0.8$ )

It should be noticed following flow peculiarities that are characteristic for EN of HBT. In the nose part of inlet cowling, supersonic zone (see Fig. 1) and, hence, shock

wave can appear at cruising flight regime. Intensity of shock wave essentially influences on the EN external drag and, appropriately, on the effective thrust. Properties of this supersonic zone depend both on the shape of the inlet cowling nose part and on midsection diameter and position. During EN aerodynamic design, it seems reasonable to choose control geometrical parameter values so as, at cruising flight regimes, to minimize intensity of shock waves at the cowling outer surface and, in the limiting case, to exclude the possibility of supersonic zone. The shape of the cowling nose part is one of parameters that define the character of flow in inlet duct at take-off regimes. Unfortunate choice of control geometrical parameter values can lead, in particular, to flow separations in the inlet inner duct and hence to illegal growth of flow non-uniformity at the engine entrance. It is visible in Fig. 2 that shows streamlines and Mach number field, which correspond to take-off engine working regime at zero velocity of the main stream and at crosswind speed  $w = 18$  m/s, for one of intermediate EN geometry variants.

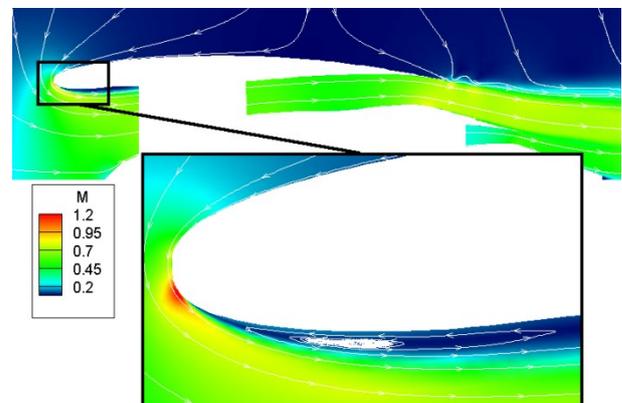


Fig. 2. Mach number field and streamlines, take-off regime at crosswind speed ( $M_\infty = 0.0$ ,  $w = 18$  m/s)

### 2.2 Decisive Criterion

Inlet design has evident compromise character because of necessity to provide stable and efficient work of cruise power plant at all flight regimes. In such situation, the choice of decisive criterion (objective function) has a definite difficulty because different objective functions has optimum in different zones of control parameter and control parameters often have an opposite influence on these functions.

For example, growth of inlet lip thickness favorably influences on flow non-uniformity degree at the engine entrance for take-off regime with cross wind, but increases EN external drag at cruising flight regime.

The current paper proposes to take a power plant effective thrust  $P_{eff}$  at cruising flight regime as a decisive criterion (objective function) for choosing the optimal geometry of isolated engine nacelle. The reason of such choice is that designed engine is oriented to the family of long-haul aircraft. Cruising flight regime is the most prolonged for these aircrafts. It is assumed that optimum of chosen objective function is determined with taking into account a number of design and gasdynamic limitations. These include, in particular, necessity to satisfy normative requirements of pressure coefficient and flow non-uniformity level at the engine entrance for all flight regimes, flow without separation inside the inlet, guaranteeing the stable work of engine at critical angles of attack and at cross wind. In fact, the problem about optimal aerodynamic design of isolated EN is reduced to conditional one-criterion optimization of chosen objective function  $P_{eff}(\vec{G})$ , where  $\vec{G} = \{x_1, x_2, \dots, x_{N_{par}}\}$  is the vector of control geometrical parameters  $x_i$ ,  $N_{par}$  is the number of control geometrical parameters. At that both calculation of objective function values and verification of all existing gasdynamic limitations are performed using numerical calculation of viscid gas flow around EN for each given series of control parameters  $\vec{G}$  and for flight regime. Briefly, the problem about optimal aerodynamic design of EN is formulated as follows:

it's necessary to find the point

$$\vec{G}^{(opt)} = \{x_1^{(opt)}, x_2^{(opt)}, \dots, x_{N_{par}}^{(opt)}\},$$

where the objective function  $P_{eff}(\vec{G})$  achieves to its maximum:

$$\max \left\{ P_{\text{eff}}(\vec{G}^{(opt)}) \right\}, \text{ where } \vec{G}^{(opt)} \subset \Omega.$$

Domain  $\Omega$  is a bounded feasible region of possible control geometrical parameters  $x_i$ ,  $i=1 \div N_{par}$ . Boundaries of  $\Omega$  are given by following inequality system:

$$\Omega = \begin{cases} x_i^{(\min)} \leq x_i \leq x_i^{(\max)}, & i = 1 \div N_{par} \\ f_j(\vec{G}) \leq 0, & j = 1 \div N_2 \end{cases}$$

### 2.3 Mathematical Model of the Inlet

One of the most important stage of optimization problem, which mainly determines the problem complicity and whole work content, is to choose a series of control parameters.

Fig. 3 demonstrates the main geometrical parameters that influence on aerodynamic properties of the inlet.

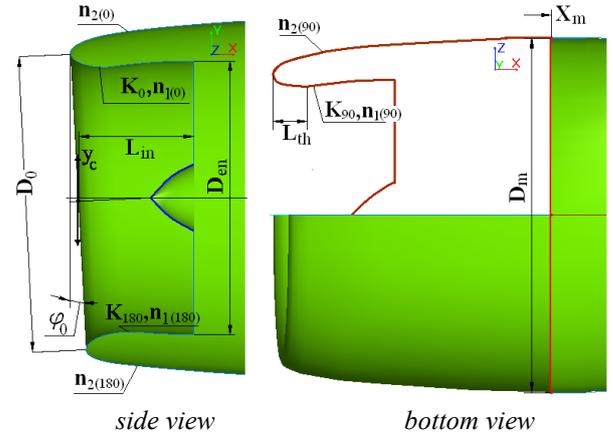


Fig. 3. Parametric model of inlet

Fig. 3 uses following designations:

- $D_0$  is a diameter of inlet leading edge;
- $K_0, K_{180}, K_{90}$  are thickness coefficients of the upper, down and lateral inlet lips;
- $D_{en}$  is a diameter of engine entrance;
- $L_{in}$  is inlet length;
- $L_{th}$  is a distance from the leading edge to the inlet throat;
- $\varphi_0$  is inlet inclination angle;
- $n_{1(0)}, n_{1(180)}, n_{1(90)}$  are coefficients defined the inner surface geometry of the upper, down and lateral inlet cowlings;
- $n_{2(0)}, n_{2(180)}, n_{2(90)}$  are coefficients defined the outer surface geometry of the upper, down and lateral inlet cowlings;
- $D_m$  is a diameter of EN midsection;
- $X_m$  is a position of EN midsection;
- $y_c$  is a height of inlet axis position.

Inlet thickness coefficients  $K_i$  of  $i$ -section is calculated using the formula  $K_i = (D_0 / 2R_{th(i)} - 1) \cdot 100\%$ , where  $R_{th(i)}$  is a distance from the  $i$ -section throat to inlet axis. The shape of outer and inner parts of cowling is

determined using power functions [3]. Their exponents are the coefficients  $n_{1(i)}$  and  $n_{2(i)}$ . For example, the coordinates of upper cowling inner part are given by the formula:

$$y = \frac{2R_{th} - D_0}{2} \left[ 2 \frac{x}{L_{th}} \left( 1 - \frac{x}{2L_{th}} \right) \right]^{n_{1(0)}}$$

and outer part by the formula:

$$y = \frac{D_m - D_0}{2} \left[ 2 \frac{x}{X_m} \left( 1 - \frac{x}{2L_{in}} \right) \right]^{n_{2(0)}}$$

By means of varying the coefficient values  $n_{1(0)}$  and  $n_{2(0)}$ , the cowling geometry can be considerably varied. It is visible in Fig. 4 that demonstrates the influence of coefficient  $n_{2(0)}$  on the shape of the upper cowling outer part.

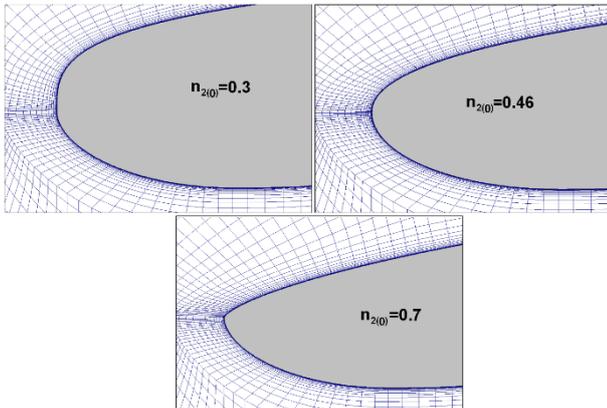


Fig. 4. Influence of geometrical parameter  $n_2$  on the shape of inlet cowling

### 3 Methodology of Field and Integral Characteristics Calculation

#### 3.1 Calculation Method

All calculations are performed using solver ZEUS [4; 5], which is part of TsAGI in-house code EWT-TsAGI [6]. The EWT-TsAGI application package realizes a conception of “Electronic Wind Tunnel” [7]. It provides possibilities to simulate a wide range of stationary or non-stationary gas flows with complex geometry on the basis of Euler, Navier-Stokes, LES or RANS equations. Several differential models of turbulence are available: (q- $\omega$ )-model by Coakly [8], SST-model by Menter [9],  $v_t$ -model by Spalart and Allmaras [10]. The calculations are performed

on multiblock structured grid with hexahedral cells.

The solver is based on the finite-volume numerical method that has the second-order approximation in all variables and is based on the Godunov-type TVD scheme for approximation of convective fluxes (MUSCL) [11; 12; 13], the central-difference approximation of diffusive fluxes and two-layer point-implicit approximation of source terms. Detailed description of this method is given in [6].

Stationary solution is obtained using a linearized implicit scheme [14]. The implicit scheme is written in delta-form [15] and has the first approximation order in time. In the current work, Reynolds equation system closed by SST turbulence model is solved.

#### 3.2 Boundary and Initial Conditions

Main flow parameters are given and non-reflecting boundary condition is formulated at the outer boundary of calculation domain. A boundary condition of heat-insulated non-slipping wall is given at solid surfaces. Total pressure and total temperature corresponded to engine work regime are given at the entrance of each nozzle contour, static pressure at the engine entrance is taken as constant. Pressure value is corrected during the calculation so as to provide the balance of air consumption through the throat and inlet.

#### 3.3 Determination of Inlet Integral Parameters

Requirements to the inlet are often contradictory and, therefore, optimization degree of inlet, which is chosen for a concrete aircraft, depends on compromise solution correctness.

Following requirements are formulated for inlet:

- high total pressure loss factor at the engine entrance for all regimes;
- small external drag;
- a rather uniform pressure field at all regimes that is a necessary condition for stable work of engine.

The main aerodynamic characteristics of the inlet are:

- total pressure recovery ratio  $\nu = \frac{p_{0en}}{p_{0\infty}}$ ,

where  $p_{0en}$  is average total pressure before the engine,  $p_{0\infty}$  is total pressure of undisturbed flow;

- total pressure loss factor

$$\delta = \frac{p_{0\infty} - p_{0en}}{p_{0\infty}} = 1 - \nu;$$

- discharge coefficient  $f = \frac{F_{\infty}}{F_0}$ , where  $F_0$

is an inlet surface at the leading edge,  $F_{\infty}$  is surface of appropriate jet that comes into the leading edge of the inlet;

- relative velocity at the entrance into inlet throat  $\bar{V}_{th} = \frac{V_{th}}{V_{\infty}}$  that is equal to relation

of velocity in the inlet throat ( $V_{th}$ ) to main flow velocity  $V_{\infty}$  of undisturbed flow;

- azimuthal  $\Delta\sigma_0$  and radial  $\Delta\sigma_r$  non-uniformities.

The calculation of azimuthal and radial non-uniformities is performed with taking into account the boundary layer using the methodology that has been described in detail in [16].

## 4 Automatic Modification of Geometry and Calculation Grid

### 4.1 Geometry Creation

After creating a parametrized mathematical model of EN, it is necessary to organize an automatic modification of geometry and calculation grid, according to control geometrical parameters of model. This process includes two stages: modification of geometrical model in CAD system and automatic regeneration of calculation grid using grid-generator on basis of modified geometrical model.

Process automation is performed using scripts. A script#1 is written during the initial creation of the geometry in CAD-system. Then, automatic modification of EN shape is performed using this script. The script text includes all geometrical model sizes and each size is a value of definite variable declared in script. As a result of script running, a file with geometrical model with given values of control geometrical parameters appears.

### 4.2 Grid Creation

A structured multi-block 3D calculation grid is used in the calculation of flow field around the EN. Using basic geometrical model, a calculation grid is generated in each block. Half EN model is used (a symmetry boundary condition is formulated in XY plane) at cruising and take-off flight regimes; total model is considered for regime with cross wind. Fig. 5 shows a fragment of the computational grid near the inlet.

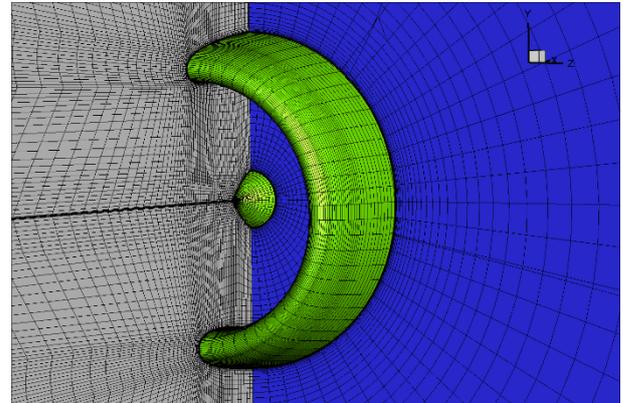


Fig. 5. Fragment of the computational grid near the inlet

Process automation is performed using scripts. A script#1 is written during the initial creation of the geometry in CAD-system. Then, automatic modification of EN shape is performed using this script. The script text includes all geometrical model sizes and each size is a value of definite variable declared in script. As a result of script running, a file with geometrical model with given values of control geometrical parameters appears.

After generating the calculation grid for one geometrical model, the grid is modified for another geometrical model by associating nodes and edges of each block of old (basic) grid to control points and curves of the new geometry.

For that, a modified geometry in IGES format is imported, then association is performed and new 3D grid is generated. All these actions are written in the script#2 that is the main tool for automatic modification of calculation grid.

For automation of process above of geometrical model and calculation grid modification, a control module generated on basis of high-level programming language Python [17] is used. As entrance parameters, the module uses all necessary parameters of the new geometrical model, modifies both scripts is it is necessary and runs them in series. Automatic generation of geometry and calculation grid provides both essential acceleration of preparing the initial data for numerical calculations and entirely excludes a possibility of accidental errors that inevitably arise in mass manual developing the grids.

## 5 Choosing optimal values of control geometrical parameters

Optimal design is performed on basis of numerical parametrical calculations of viscid gas flow around EN. In space of control parameters, the process of approaching to optimal value of objective function is defined using an algorithm of extremum search that is known as coordinate descent method [18]. One of its advantages is evidence of its convergence process. The same important property of the method is possibility to grade objective function calculation inaccuracies that are consequences of both non-stationary phenomena and grid dependence of used numerical method.

In comparison of nozzle optimization, choice of inlet shape, which has aerodynamic efficiency, is more complicated problem. First of all, it is because problem dimension increases more than two times. It leads to essentially non-linear growth of difficulties connected with search of conventional optimum of objective function. Simultaneously, for optimization of inlet geometry, it is necessary to take into account a great number of gasdynamic limitations. Check of limitation satisfaction inevitably demands to use additional computational and time resources. In addition, it should be notices that necessity to provide

stable work of power plant at different flight regimes with non-zero attack and sideslip angles excludes possibility of axisymmetric calculations. Hence, to calculate objective function values and to check gasdynamic limitation satisfaction, calculation of flowfield around EN in more complicated and resource-intensive 3D formulation is necessary.

At the stage of preliminary calculations (axisymmetric EN), an unexpected peculiarity of considered EN has been detected: geometrical variations of inlet inner part don't practically influence on external drag of EN and on effective thrust. This property is shown in Fig. 6, where linear approximation results (dotted line) of numerical relative effective thrust  $\bar{P}_{eff}$  are presented for axisymmetric EN at cruising flight regime (triangles). It is obvious that objective function remain practically the same in wide range of thickness coefficient of inlet lip  $K$ .

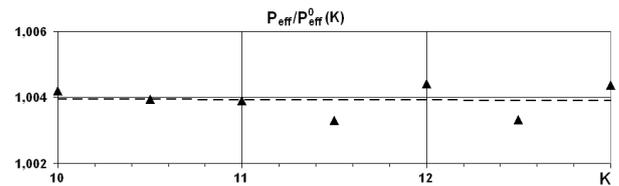


Fig. 6. Dependency of relative effective thrust upon thickness coefficient of inlet lip (axisymmetric EN, cruising regime)

As a result, inlet shape optimization problem has been broken into two subproblems. The first subproblem purpose is a choice of control geometrical parameter values that define the shape of inlet inner duct. At that, the main attention is paid to satisfaction of gasdynamic limitations (flow without separation inside the inlet at all flight regimes, including take-off regime with cross-wind and to satisfaction of normative requirements for pressure recovery coefficient and flow non-uniformity level at the engine entrance. Then, with the same shape of inlet inner duct, the outer shape that provides maximum of effective thrust at cruising flight regime is defined.

In framework of EN mathematical model chosen in the current work, variation of inlet inner duct shape depends upon 8 geometrical parameters:  $D_0$  is a diameter of inlet leading edge,  $K_0$ ,  $K_{180}$ ,  $K_{90}$  are thickness coefficients of

the upper, down and lateral cowlings of inlet,  $L_{th}$  is distance between the leading edge and inlet throttle, and  $n_{1(0)}$ ,  $n_{1(180)}$ ,  $n_{1(90)}$  are coefficients that define inner surface geometry of the upper, down and lateral cowlings of inlet. Optimization result of inlet inner duct shape is shown in Fig. 7, where total pressure fields and pressure recovery coefficient dependencies upon cross-wind velocity at the engine entrance are presented for main (Base) and optimal (Optim) variants of EN. It is obvious that "Base" variant at cross-wind velocity  $w > 16$  m/sec gives invalid decrease of pressure recovery coefficient and flow separation. The inlet designed using the methodology proposed in the current paper provides both flow without separation and satisfaction of all normative requirements for flow non-uniformity level and pressure recovery coefficient up to cross-wind velocity  $w = 20$  m/sec.

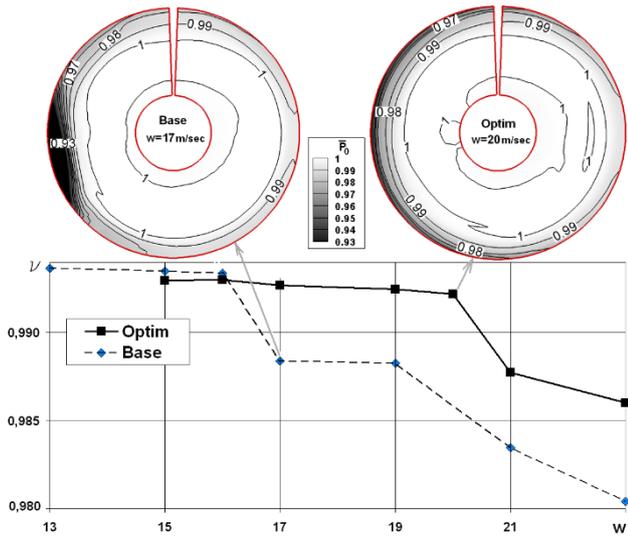


Fig. 7. Pressure recovery coefficient dependency upon cross-wind velocity for different variants of EN

Flow peculiarities in the inlet inner duct are shown in Fig. 8, where streamlines and Mach number fields near inlet surface, which correspond to basic and optimal variants of EN are shown for regime  $M_\infty = 0$  with cross-wind.

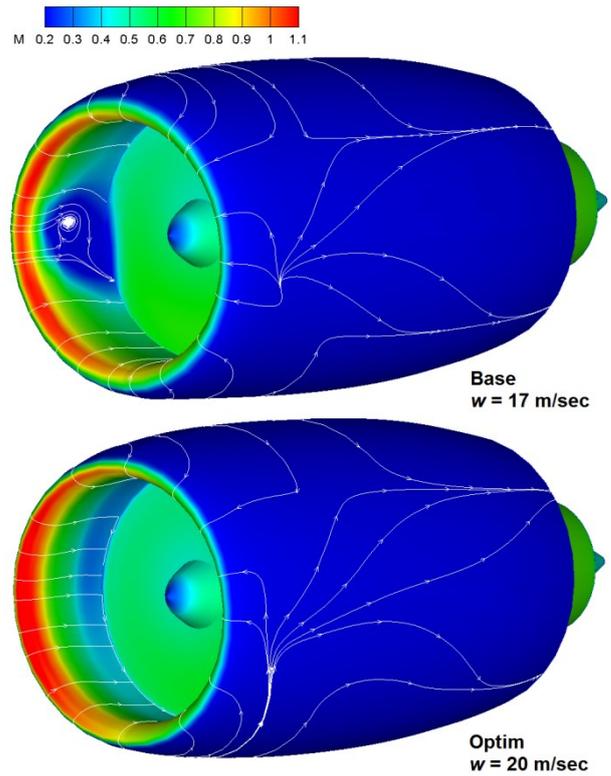


Fig. 8. Streamlines and Mach number fields for regime  $M_\infty = 0$  with cross-wind

At the final stage of EN design, geometry of inlet outer surfaces is chosen to provide maximal value of effective thrust at cruising flight regime. Outer shapes of EN nose part, in accordance with chosen mathematical model, are defined by control geometrical parameters  $n_{2(0)}$ ,  $n_{2(90)}$ ,  $n_{2(180)}$ , which give the outer contour shape of the upper, down and lateral cowlings of the inlet. To determine optimal values of these parameters, a steep ascent method [19], which provides adequate choice of trajectory approaching to extremum, when calculation of objective function values has an accidental error, is used. As a result, growth of objective function due to inlet optimization is 1.69 % and decrease of external drag is 9.6 % relatively the basic variant of EN.

It should be noticed that EN shape optimization effect is obvious in a rather wide range of flight regimes. For example, the chart in Fig. 9 shows that relative growth of effective thrust varies from 1.5 % to 1.7 % and decrease of relative external drag is 8–11 % at cruising flight regime for operating range of attack angles (grey color in Figure). In addition, optimal EN has essentially less maximal Mach

number at the outer surface for whole range of admissible angles of attack. It is obvious in Fig. 10.

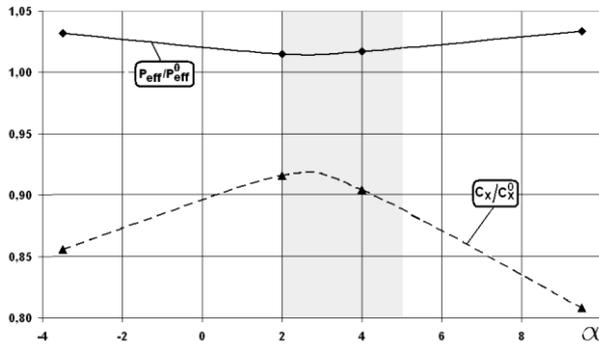


Fig. 9. Attack angle influence upon relative values of effective thrust and external drag (cruising regime)

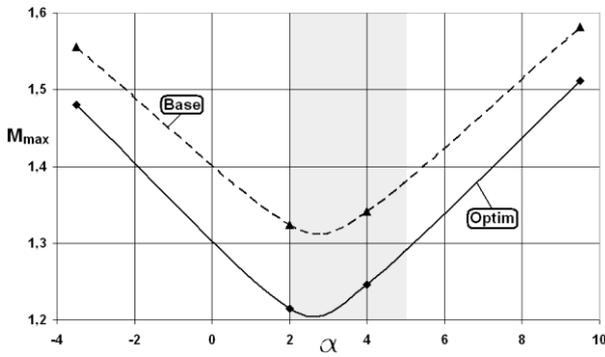


Fig. 10. Attack angle influence upon maximal values of Mach numbers at the inlet outer surface (cruising regime)

Effect of inlet shape optimization is especially obvious for critical angles of attack (see Fig. 9). For example,  $P_{eff}/P_{eff}^0 = 1.032$  (growth 3.2%) and  $C_x/C_x^0 = 0.855$  (decrease by 14.5%) at  $\alpha = -3.5^\circ$ , and, correspondingly,  $P_{eff}/P_{eff}^0 = 1.034$  (growth 3.4%) and  $C_x/C_x^0 = 0.807$  (decrease by 19.3%) at  $\alpha = 9.5^\circ$ . It can be explained by the fact that EN obtained during optimal design (in contrast to basic one) satisfies to all gasdynamic limitations and, in particular, to requirement that the external flow around EN is without separation for admissible flight regimes. It is obvious in Fig. 11 and 12.

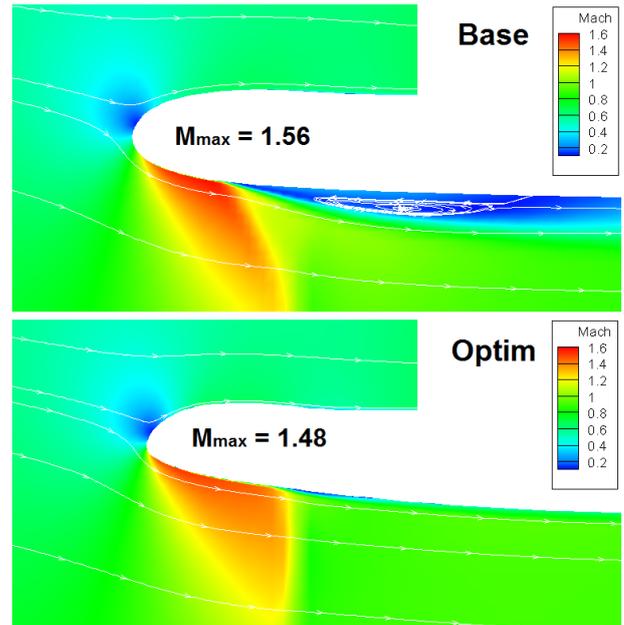


Fig. 11. Streamlines and Mach number fields near the down cowling for different variants of the inlet (cruising regime,  $\alpha = -3.5^\circ$ )

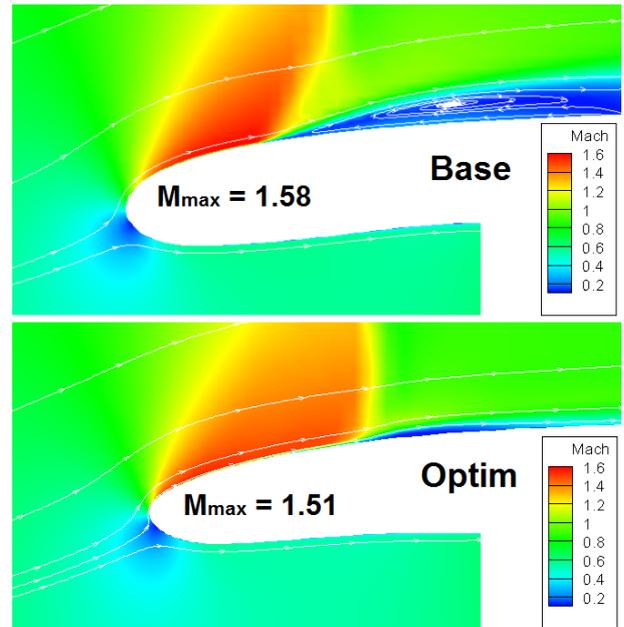


Fig. 12. Streamlines and Mach number fields near the upper cowling for different variants of the inlet (cruising regime,  $\alpha = 9.5^\circ$ )

## 6 Conclusion

To increase the aircraft power plant efficiency, an aerodynamic design methodology that is based on numerical calculations and optimized the inner and outer shapes of the cruise EN inlet has been proposed. The problem to create the EN geometry with ideal aerodynamics is considered in a strict

formulation with obligatory taking into account a large number of design and gasdynamic limitations, which are peculiar to considered variant of HBT and to its working conditions. As a decisive criterion, a value of effective thrust at cruising flight regime has been proposed to use. To choose the trajectory approaching to optimum in the space of control parameters, algorithms that provide adequate solution, when accidental errors are possible in calculations of objective function values are used. Using the algorithms for automatic modification of geometry and calculation grid has permitted to exclude subjectivism and to minimize errors of manual preparing the initial data.

Approbation and estimation of proposed methodology workability and efficiency have been performed for optimizing the inlet of isolated EN of HBT. A mathematical model of inlet has been developed. It includes 13 control geometrical parameters. An accessible region of parameters variation has been given by a series of design and gasdynamic limitations. Integral aerodynamic characteristics have been determined on basis of numerical calculations of 3D flow around EN using Reynolds-averaged Navier-Stokes equation. Code ZEUS that is a part of EWT-TsAGI application package has been used.

Proposed decomposition of the problem has essentially diminished volume of time and computational resources that are necessary to obtain final result. Advantages of proposed algorithm for optimal aerodynamic design the EN are demonstrated by comparing integral characteristics of optimal EN and basic one developed in framework of usual methodology. It has been shown that, as a result of optimization, efficiency thrust has increased by 1.5–1.7 % and external drag has diminished by 8–11 % in comparison with EN “Base” variant at cruising flight regime for working conditions of attack angles. At the same time, all design limitations and requirements of stable and efficient engine work have been satisfied for all aircraft regimes. In particular, condition of flow without separation around the EN has been satisfied for cruising flight at critical angles of attack. Normative requirements for pressure

recovery coefficient and flow non-uniformity level at the engine entrance have been provided for regime with  $M_\infty = 0$  and cross-wind velocity up to a 20 m/sec.

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