THE NUMERICAL ANALYSIS OF IMPACT OF CHANGES IN FLIGHT CONDITIONS AND IN ENGINE'S REGIME AT CRUISE ON AIRPLANE'S AERODYNAMIC CHARACTERISTICS

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Abstract

The results of the work show that for advanced airplanes with high bypass ratio turbofans forces acting on propulsion system elements at cruise depend very strong on flight conditions and engine's regime and the design of propulsion systems for some mean point of typical cruise flight trajectory can lead to gain in airplane's overall fuel efficiency up to 1 %.

1 Introduction

Now and in a foreseeable future propulsion systems of subsonic long-range passenger and transport airplanes will be still grounded on turbofan with high but moderate (10-12) bypass ratio (HBR) and classical mature solutions for engine's architecture and its location on a pylon underneath of the wing.

It is natural, that at such approach, despite use of newest technologies and materials for engine's parts and systems, for appreciable increase in airplane's overall fuel efficiency it is necessary to eliminate all potential reasons of lowering airplane's aerodynamic characteristics, particularly remove negative airframe-propulsion aerodynamic interference. Objectively this problem is linked with absolute and relative increase in sizes of the main propulsion system with growth of turbofan's bypass ratio for modern and perspective airplanes as it can be seen on Fig. 1.

Fig. 1. Change of relative sizes of the main propulsion system for airplanes of different generations

As can be shown, one of the negative feature of the airframe-propulsion system interference is a very strong dependence of forces acting on powerplant's elements from flight conditions and engine's regime at cruise.

To solve this problem the CIAM's developed technique was used, which allow to calculate 3D viscous flow around airplane with simulation of turbofan engine based on its full 1D thermodynamic description. Thus engine's mass flow varied with flow parameters in inlet and in nozzles and, in its turn, pressure distributions on powerplant elements and on adjacent airframe parts varied with engine's mass flow. Description and some examples of application of this technology may be found in works [1-4].

The results of this work show that it is reasonable to design a HBR turbofan's based powerplant for some mean point of typical cruise flight trajectory, having ensured in this point a minimum wave drag with taking into account first of all powerplant-wing interference effects.

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2 Key technologies

At a design stage of advanced long-range subsonic passenger and transport airplane's propulsion system there is a number of the problems immediately linked to the turbofan used, especially if it is also in a development stage. These problems include: increasing airframe-engine aerodynamic interference with growth of engine's bypass ratio (current values 8-9, expected values 12 - 14), which strongly influences airplane performances; restricted information about engine performances due to objective (insufficient detailed elaboration of the project), or/and organizational (confidentiality of the engine's data and mathematical model) reasons.

At the same time, airplane company has, though in restricted amount, the technical information, allowing to link airframe and engine to design powerplant. Taking this into account, it is represented expedient to have the instrument which would allow to carry out the calculations linked to the analysis of aerodynamic characteristics of arranging "engine nacelle-pylon-wing-fuselage", with engine model, allowing to consider change of its operating conditions at change of requirements of flow.

Such model should fulfill to follows requirements: to "link" of the engine based on restricted information from engine's development company; to calculate data needed for engine's simulation in CFD code (total entry mass flux and stagnation pressure and stagnation temperature an engine's nozzles) using airplane's external flow conditions and nozzle's flow coefficients.

2.1 Turbofan simulation technology

The turbofan simulation technology used in this work include core systems (applications): Turbofan Dialogue System (TDS) and Turbofan Simulation System (TSS).

The first one is intended for definition of key parameters, geometrical sizes and performances of turbofan (with mixing or/and separate flows) engine and allows to work effectively by engineer not familiar close with engine design theory and professional design tool. All engines observed can be differed by number of shafts, presence or lack fan gear etc. The TDS has hierarchical structure and include: control subsystem; design subsystem (engine's elements linking, throttling characteristics calculation etc.); real time analysis and alternatives comparison subsystem; long-term storage archives and tools for automatic links between TDS's structural elements; the dialogue support subsystem; input data control and user's action monitoring subsystems. Each subsystem, in its turn, has hierarchical structure and consists of subsystem's control module and modules implementing special operations (data input/substitution, simulation, visualization etc).

The TDS – user "query-answer" subsystem is developed in terms gas turbine engine design practice and it is clear for understanding and does not require deep knowledge in engine design theory.

An example of data necessary for TDS (altitude, Mach number, difference from ISA, thrust, mass flow rates, total pressures and temperatures) is resulted in Table 1.

Table 1. Data necessary for turbofan's flight regimes approximation in the TDS

Altitude	Mach	ΔTamb	Thrust	W2A	W8	P8	T8	W18	P18	T18
ft										
0	0.000	0.000	7.378	2.675	2.833	3.649	1.226	2.674	3.032	1.177
0	0.250	0.000	5.870	2.935	3.086	3.812	1.246	2.935	3.214	1.195
37000	0.800	0.000	1.429	1.079	1.166	1.193	1.148	1.072	1.082	1.027
37000	0.800	0.000	1.357	1.068	1.144	1.157	1.116	1.061	1.069	1.022
37000	0.800	0.000	1.286	1.055	1.123	1.125	1.086	1.049	1.055	1.018
37000	0.800	0.000	1.214	1.043	1.097	1.092	1.059	1.038	1.042	1.013
37000	0.800	0.000	1.143	1.029	1.068	1.060	1.036	1.026	1.028	1.009
37000	0.800	0.000	1.071	1.015	1.036	1.030	1.017	1.013	1.014	1.004
37000	0.800	0.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
37000	0.800	0.000	0.929	0.984	0.961	0.971	0.986	0.987	0.986	0.996
37000	0.800	0.000	0.857	0.968	0.918	0.942	0.973	0.973	0.971	0.991
37000	0.800	0.000	0.714	0.933	0.832	0.888	0.947	0.942	0.941	0.982
37000	0.800	0.000	0.571	0.895	0.736	0.839	0.927	0.909	0.910	0.971
37000	0.800	0.000	0.429	0.852	0.619	0.794	0.938	0.872	0.877	0.961
37000	0.800	0.000	0.286	0.802	0.497	0.750	0.944	0.828	0.842	0.950
37000	0.800	0.000	0.143	0.743	0.385	0.722	0.929	0.775	0.803	0.937

The sequence of queries is shaped automatically under the certain logic according to which the answer to any query defines sequence of further queries. Thus, feeding into of all input information necessary for calculation and lack of superfluous data is ensured. Important feature of the TDS is embedded databases (archives), containing the information about design parameters and characteristics of exiting engines (CFM56, PS90 etc.). During the work with TDS it is possible to copy the information from one archive in another. This possibility is used for linking of new engine taking into account parameters from the old one (linking based on a prototype). For this purpose the needed (prototype) engine is chosen from TDS's database with suitable parameters, copied under a new name and then in dialog mode the new linking requirements set up and appropriate calculation is carried out.

An example of TDS's basic GUI ensuring the gas turbine engine (GTE) mathematical model (MM) creation and its characteristics calculation are shown in Fig. 2.

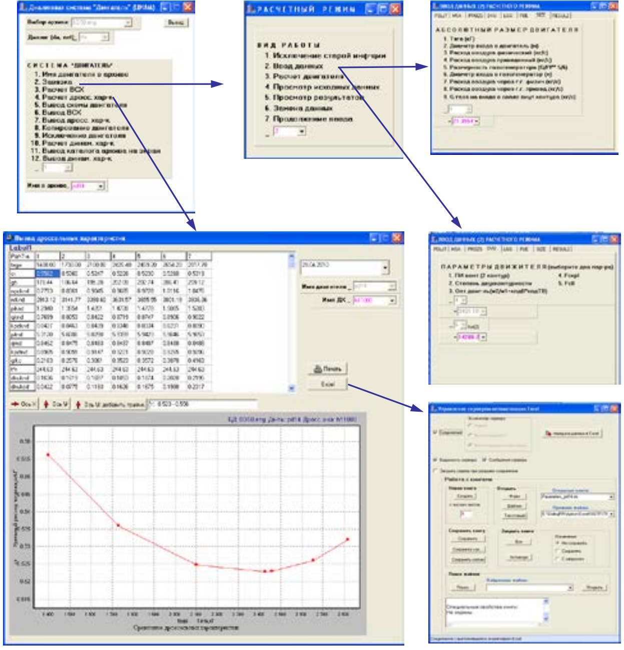


Fig. 2. The examples of TDS's basic GUI

The main result of TDS run is a data file for the TSS application allowing to define the turbofan's thermodynamic parameters in different flight conditions and for various regulation parameters (thrust, fuel consumption, etc.).

One of the main TDS's feature is active use of the generalized performances of the engine components (fan, compressors and turbines), that essentially facilitates and speeds up creation of GTE MM and improves it reliability. If it is necessary to increase reliability of definition of the engine performances the generalized component's performances can be substituted by more exact experimental or computational ones.

Comparison of TSS's calculated and the turbofan's input parameters is shown in Fig.3.

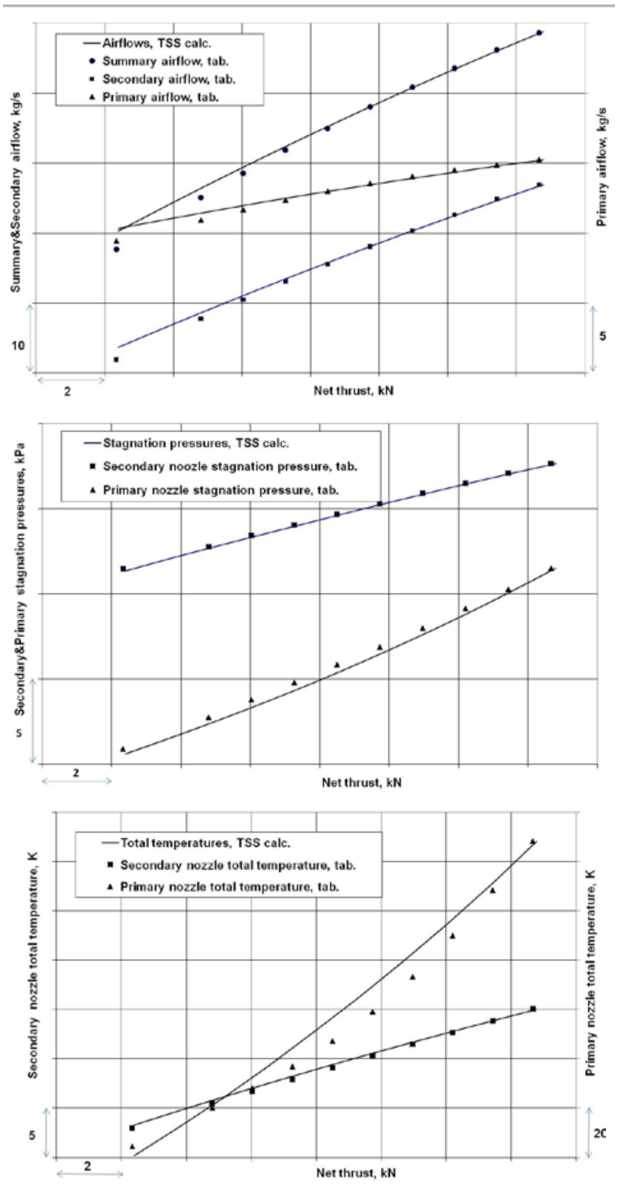


Fig. 3. Comparison of turbofan's input and TSS's calculated data

2.2 Airplane aerodynamic performance simulation technology

The numerical method based on well-known Godunov finite-difference scheme [5], developed in the beginning of 60th years for the decision non-stationary and stationary gasdynamic problems. Distinctive feature of this scheme is use of the exact decision of one-dimensional self-similar Riemann problem (gasdynamic discontinuity decay) for definition of average flow parameters of on sides of cells. The subsequent improvements of this scheme including increase of the order of approximation on space (with preservation of monotony for irregular and non-uniform meshes) and on time, have made the modified Godunov's scheme reliable and effective tool for decision of the broad range of aerodynamic problems. Opportunities of this scheme became even more in its implicit viscous variants allowing to calculate flows with Spalart-Allmaras [6], $k-\varepsilon$ [7] and SST [8] turbulent models.

In brief, applied numerical method includes the following steps: decomposition of calculation regions into hexahedral cells joined in blocks; defining in each cell the initial values of flow parameters (pressure, density, velocity components and turbulence parameters); defining boundary conditions (rules and the additional parameters, allowing to define mass, momentum, energy and turbulence fluxes through cell side adjoining to the region bounds); definition for every cell according to the RANS/URANS equations and special algorithms (flow parameters reconstruction, solution of the Riemann problem and etc) residuals (side's sum) of the mass, impulse, energy and turbulence fluxes; construction of linear equations system linking flow parameters changes in every cell with the ones in the cell's neighbors (defining by the finite-difference stencil) and with the cell's residual; iterative (by point-to-point Gauss-Zeidel method) solution of the system to find values of the flow parameters changes in each cell; calculation using these changes flow parameters on new iteration; evaluation in some corresponding norms residuals and prescribed flow characteristics (mass fluxes, forces coefficients and etc).

The CIAM's in house code Cobra based the numerical method mentioned above include: RANS/URANS solvers in Cartesian coordinate system; explicit/implicit time integration; second order spatial/time accuracy; multi-block structured fixed/moving mesh; parallel capability (shared/distributed memory);different turbulence model (Spalart-Allmaras, $k-\varepsilon$, and SST); extended wall function; different types of boundary conditions (freestream, viscous, inviscid and perforated walls, pressure inlet, pressure exit, flow exit, mass flux, normal velocity and etc).

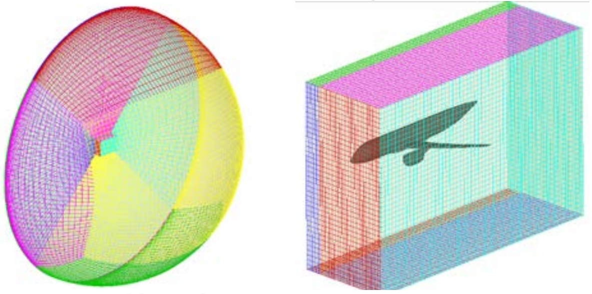
One of most useful features of the code are: high possible Courant number value (up to 1000); effective usage of the memory (up to 5, 000, 000 mesh cells for 1 Gb RAM); near linear parallel computation speed-up factor; multiplatform for Linux and Windows realization.

2.3 CFD problem statement

The A320-type subsonic passenger airplane considered in the work had classical powerplant configuration with HBR (m ~ 8.5) turbofan on a pylon underneath the wing.

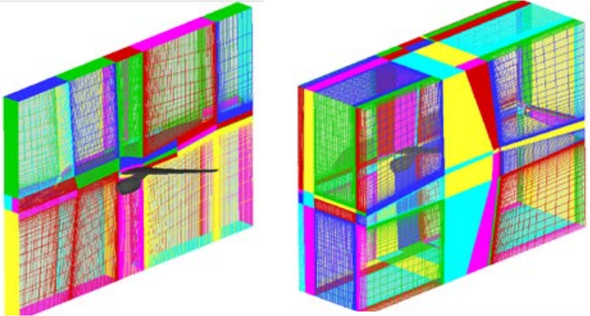
For the flow calculation around the airplane "not matching" mesh technology was used. This approach allowing to decouple topologies of structured meshes in different parts of computational region that gives the powerful possibility to control allocation of the cells in space and to focus them in the most important for a solved problem places.

The computational region and mesh used in the work are illustrated in Fig.4.



External bound　　Internal bounds

External subregion: ~2% of cells



1st part: ~17% of cells　　2nd part: ~81% of cells

Internal subregion: ~98% of cells

Fig. 4. Calculation region and mesh used: total cells number ~11.5 millions

As can be seen calculation region has been divided on exterior (bordering on to an undisturbed flow) and interior subregions with very different mesh topology and cells number.

Diameter of exterior subregion made ~18 fuselage’s lengths, and the maximum longitudinal size of the interior subregion containing the airplane, was equal to ~2 fuselage lengths.

The interior part of the calculation region is in its turn divided on two parts with different topology and cells number, first of which borders on to the airplane’s symmetry plane and contains fuselage and wing’s root part, and second one contains main part of the wing with the engine.

The sizes near wall cells were chosen such, that in the cruise conditions to ensure magnitude of y^+ parameter over the range 50-150, necessary for application of the law of a wall. The turbulence model used in this work was well-known Spallart-Allmaras model [6].

Due to the subregion’s structure it was possible to concentrate ~81 % cells around main part of the wing with the engine and, thereby, to increase quality of calculation results.

Engine simulation was carried out with use of the boundary conditions set on surfaces displayed on Fig. 5.

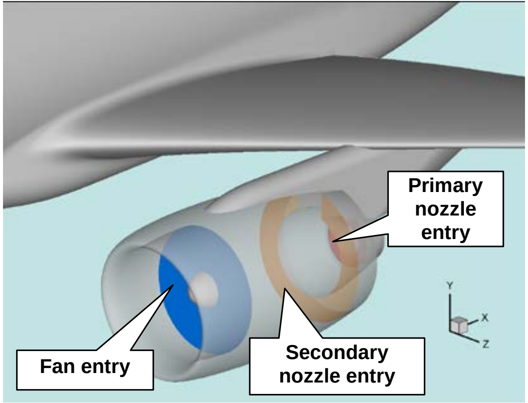


Fig. 5. Turbofan’s surfaces for boundary conditions

Conditions applied on different subregion’s and configuration’s bounds are shown in Table 2.

Table 2. Boundary conditions

Bound	Condition
External bound	Non-reflected free stream
Symmetry plane	Symmetry
Air plane’s surfaces	No sleep
Topology's rupture bounds	Implementation of conservation laws
Fan entry	Mass of airflow
Primary and secondary nozzle entry	Total pressure and total temperature

The main features of the turbofan simulation in the work are the follows:

- On the initial stage of flow convergence around the airplane fixed values of entry airflow and nozzle’s total parameters, calculated by the TSS application for given engine’s internal thrust in an undisturbed flow, are supported.
- At the completing stage of flow convergence around the airplane the values of entry airflow and nozzle’s total parameters were calculated at every convergence step by the TSS application for given engine’s internal thrust, taking into account equality of masses of entry air and exhaust gases, minus masses of fuel and air bleedings.

For evaluation of aerodynamic forces on powerplant its surfaces were divided into the parts displayed in Fig. 6 by different colors.

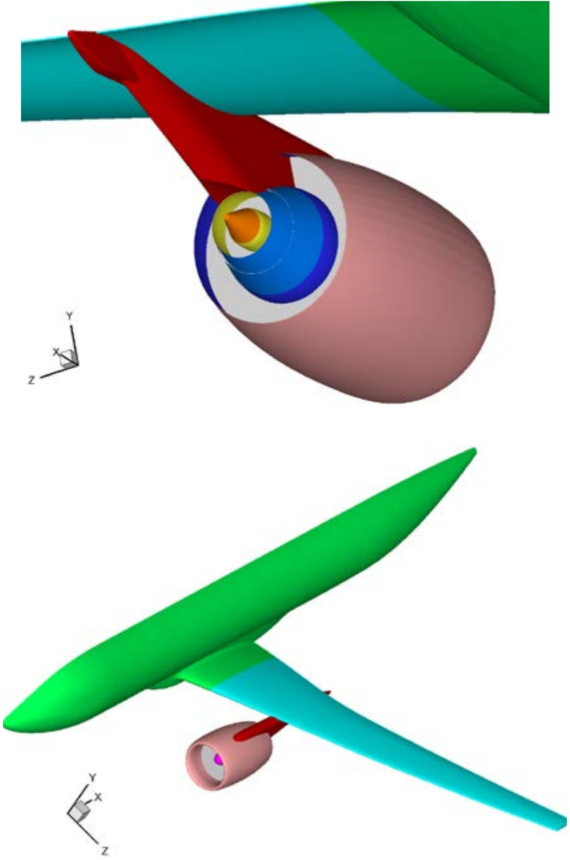


Fig. 6. Parts of the powerplant and airplane for aerodynamic forces evaluation

3 CFD calculation results

The analyzed flight conditions are presented in Table 3.

Table 3. Flight conditions

Mach number	Altitude, ft	Relative angle of attack $\Delta\overline{\alpha} = (\alpha - \alpha_{opt})/\alpha_{opt}$
0.80	35 000	-2.5,-2.0, -1.0, 0, +0.5

Some results of the calculations are shown in Fig 7 and Fig. 8.

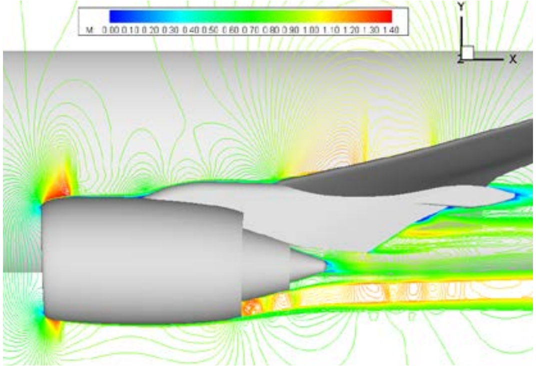


Fig. 7. Mach number isolines at cruise in plane which is passing through engine's axis, $\alpha = \alpha_{opt}$

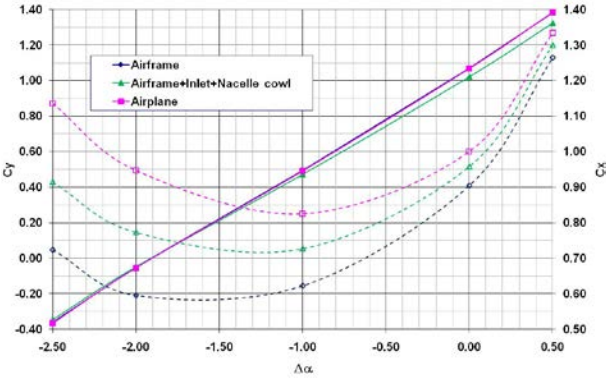


Fig. 8. Relative lift $\overline{C}_y = C_y / C_{yref}$ and drag $\overline{C}_x = C_x / C_{xref}$ coefficients as functions of $\Delta\overline{\alpha}$ for different airframe and powerplant's elements combinations

4. The impact of changes of airplane's weight at cruise on its aerodynamic quality

The results of CFD analysis can be used for the solution of a problem of impact of changes of airplane's weight at cruise on its aerodynamic quality.

Possible airplane's cruise trajectories are shown schematically in Fig.9.

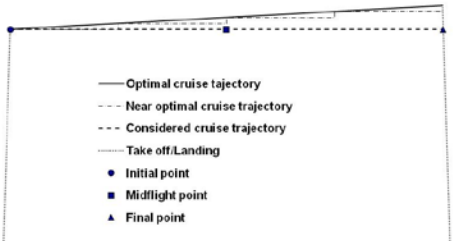


Fig. 9. Possible cruise flight trajectories and some of it points: 1- initial, 2- midflight, 3-final.

It is known, that the cruise flight with constant angle of attack and gradual climb is the most fuel effective. However due to some limitations the real cruise flights are usually carried out with only few large segments of constant altitude and the airplane's angle of attack on every of this segments decrease gradually due to fuel consumption.

To estimate maximum negative influence of an angle of attack on an airplane's aerodynamic characteristics we will consider cruise flight with constant altitude 35 000 ft. Three sequential points on this trajectory (initial, midflight and final) corresponds to different airplane weights due to fuel consumption.

According to an estimation of CIAM's specialists for distance of 5000 km the airplane's weight decrease in midflight and final points will be ~9% and ~18%.

With the use of $\overline{C}_y(\Delta\overline{\alpha})$ and $\overline{C}_x(\Delta\overline{\alpha})$ relations it is possible to find, as it is shown in Fig. 10, that decreases of angles of attack $\Delta\overline{\alpha}$ corresponding to changes of the airplane's weights mentioned above were ~0.166 и ~0.331 for midflight and final points respectively.

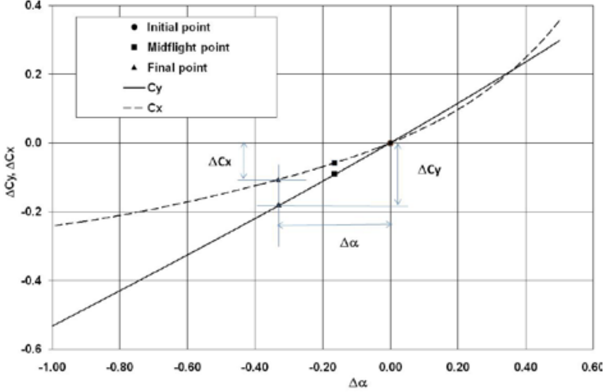
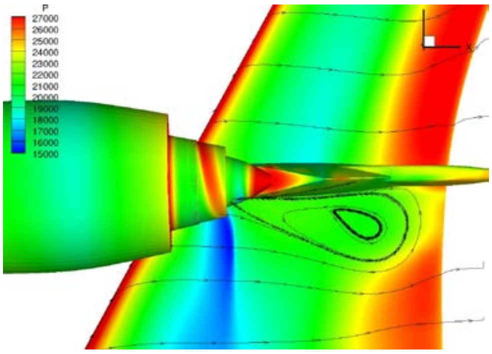
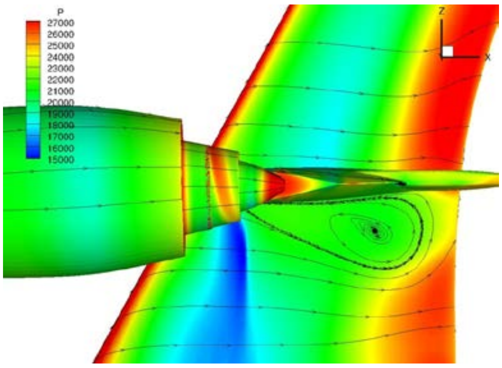


Fig. 10.Evaluation of changes of relative angles of attack and drag coefficients in the midflight and final points

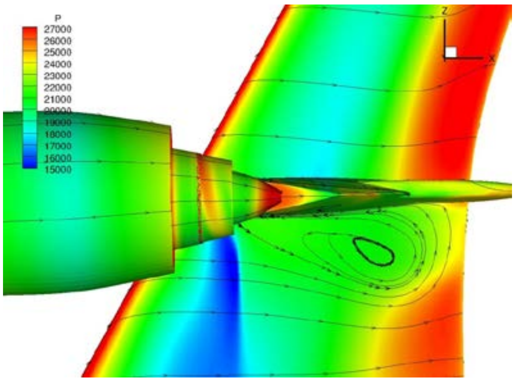
With use of above mentioned simulation technologies, including CFD code Cobra with simultaneously correction of engine parameters by the TSS application, flow around the airplane was calculated for different cruise flight points. Some results of the calculations are shown in Fig. 11-13 and in Table 4.



Initial point: $\Delta\bar{\alpha}=0$



Midflight point: $\Delta\bar{\alpha}=-0.167$



Final point: $\Delta\bar{\alpha}=-0.331$

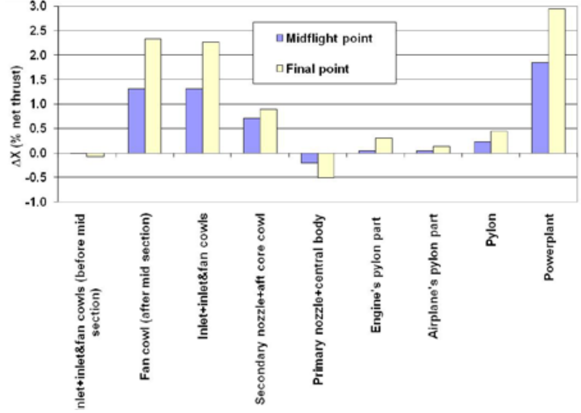
Fig. 11. Static pressure field on wing's lower side, pylon and nacelle's aft part for different cruise flight points

Table 4. Relative changes of some turbofan's parameters in different points of the cruise flight

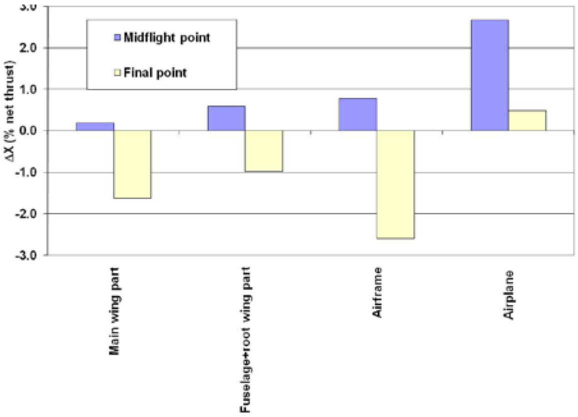
Cruse point	Engine net thrust	Total airflow	Secondary nozzle			Primary nozzle			SFC
			Airflow	Total pressure	Total temperature	Airflow	Total pressure	Total temperature	
2	0.0592	0.0148	0.0128	0.0124	0.0049	0.0352	0.0373	0.0185	0.0051
3	0.1092	0.0276	0.0241	0.0296	0.0106	0.0634	0.0669	0.0185	0.0053

From the table it can be seen that in the final cruise point turbofan's summary air flow is decreased on ~3%, and specific fuel consumption increases on ~0.5%.

The changes of relative drag forces acting on the different parts of the powerlant and the airplane for midflight and final cruise flight points are shown in Fig. 12 (Initial point's forces were taken as background).



Powerplant's components drag forces



Airplane's components drag forces

Fig. 12. Changes of relative drag forces acting on the different parts of the powerplant and the airplane for midflight and final cruise flight points

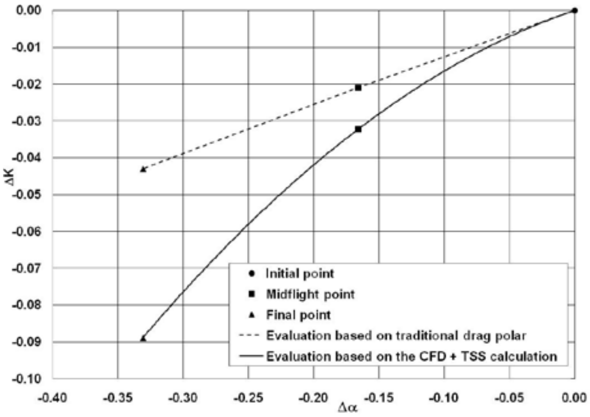


Fig. 13. Changes of relative the airplane aerodynamic quality for midflight and final cruise flight points

4 Conclusion

The results of the work show that for advanced airplanes with high bypass ratio turbofans forces acting on propulsion system elements at cruise depend very strong on flight conditions and engine's regime.

To display this dependence in the current work the problem about influence of change in weight of a modern A320-type commercial airplane on its aerodynamics has been stated for 5000's km cruise flight on constant altitude of 35000 ft with Mach number 0.80.

To solve this problem the CIAM's developed technique was used, which allow to calculate 3D viscous flow around airplane with simulation of turbofan engine based on its full 1D thermodynamic description. Thus engine's mass flow varied with flow parameters in inlet and in nozzles and, in its turn, pressure distributions on powerplant elements and on adjacent airframe parts varied with engine's mass flow.

The detailed analysis of flow around the airplane and its aerodynamic characteristics in midflight and final cruise points has shown, that with decrease of angle of attack and appropriate changes of the engine's regime (working mode):

- the total increase of powerplant drag in final point (~3% of engine's net thrust) take place defined mainly by aft part the nacelle cowl;
- the overall increase of the airplane's drag (from 0.5% to 2.6% of engine's net thrust) defined only by the powerplant's drag growth;
- the engine's mode correction approach used in this work shows additional (~4.5%) degradations of the airplane's aerodynamic quality which size is comparable to the quality reduction defined in the traditional way by means of drag polar.

The results of the work show also that it is reasonable to design a HBR turbofan's based powerplant for some mean point of typical cruise flight trajectory, having ensured in this point a minimum wave drag with taking into account first of all powerplant-wing interference effects.

More detailed analysis shows that this approach can lead to gain in airplane's overall fuel efficiency for typical cruise flight up to 1 %.

5 Acknowledgments

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