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Features of numerical simulation of the unsteady vortex flow around aircraft considering airbrake

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Abstract. The paper presented the specifics of calculating the characteristics of vortex propagation and decay processes which cause aerodynamic tail fin-buffet loads in an aircraft at incompressible subsonic flow. Analysis of numerical diffusion and stability of differencing schemes implemented in OpenFOAM software package has been carried out. Based on the obtained results, differencing schemes are selected and their modification has been done. An algorithm has been presented for combining various approaches for modelling turbulent flows (RANS-LES) by means of zonal isolation and its implementation in OpenFOAM package is carried out. A series of calculations of three-dimensional flow around an aircraft at angles of attack of 0 to 30 degree considering airbrake deflections on 60 degree are conducted. Flow separation at the airbrake side edges and upper edge result in a highly turbulent wake. The corresponding region of vortex flow affects the fin and causes buffet loads.

1. Introduction

Motion of flying vehicles in atmosphere is generally accompanied by flow separation and formation of vortex flows, which result in redistribution of pressure on the aircraft's surface and change in its aerodynamic characteristics. In a subsonic flow around an aircraft's structural elements, zones of separation flow appear behind them where flow parameters have vortex pulsation nature. Studying vortex flows and their interaction with elements of aircraft has become one of the current objectives in the field of aviation and rocket science. Subsonic flow around high-lift system and various versions of external control devices as well as flying at extreme angles of attack result in formation of vortex structures, and unsteady change of their aerodynamic characteristics. On the other hand, the vortex flows generated by various elements of an aircraft such as deflectors or airbrakes may impact control and stabilizing surfaces located in their wake causing their shaking (buffet loads) due to periodic shock loads [1]. At present, most research is focused on studying the processes of tail fin-buffet loads occurrence, in which periodic vortex wake induced by an airbrake can lead to unsteady pulsating loads on the tail fin [1-3].

Nowadays, despite rapid progress in the field of experimental investigation methods, determination of flow structures of maneuverable aircrafts remains a complex task and requires the use of expensive equipment. In this case mathematical modelling of the flow around modern aircraft is an important step of examination and in many instances serves to confirm or disprove a hypothesis describing a physical phenomenon. At present, it is possible to point out a number of current challenges in the field of determining the aerodynamic characteristics at the flow around the aircraft, which are associated with numerical modelling of vortex flows and their interaction with flight control surfaces.

2. Mathematical model

Mathematical model of an incompressible gas includes continuity equation and Navier–Stokes equations:

$$\nabla \cdot \left(\vec{V}\right) = 0 \; ;$$
$$\rho \frac{\partial\left(\vec{V}\right)}{\partial t} + \rho \vec{V} \nabla V = -\nabla p + \nabla \cdot \tau \; , \tag{1}$$

whereρ is density; $\vec{V}$ is velocity vector; p is pressure; τ is tensor of viscous stresses; t is time.

The numerical solution of the system equations (1) with finite volume method is the most promising approach to calculating aerodynamic characteristics of an aircraft. In the continuity equation, only the velocity vector is included, resulting in the absence of direct link to pressure, which in case of compressed flows is effected through density. In this study, a PISO (Pressure-Implicit with Splitting of Operators) algorithm has been chosen for linking pressure to velocity. These equations are solved under the initial and boundary conditions characteristic for the problems given. After appropriate transformation (discretization), a system of linear algebraic equations is obtained. Values of flow parameters on cell faces necessary for solving conservation equations in algebraic form are determined by means of various differencing schemes.

Since the flow is turbulent and is characterized by the presence of fine and large-scale vortex structures, an eddy-resolving approach has been used for their calculation, combining RANS (Reynolds-averaged Navier–Stokes equations) and LES (Large Eddy Simulation) methods. To close the filtered equations, i.e. to model the interaction of large vortices with fine-scale turbulence, Smagorinskysubgrid model has been used. In this model, the subgrid viscosity is calculated as follows:

$$\nu_{SGS} = \left(C_S \Delta\right)^2 \sqrt{2 S_{ij} S_{ij}} \; , \tag{2}$$

where Δ is filter size; C_S is an Smagorinsky constant; $S_{ij}$is the resolved rate of strain.

Finite volume method and various approaches to simulation of turbulent flows are implemented in many licensed commercial software packages such as ANSYS CFX, FlowVision, FloWorks, STAR-CCM etc. However, they are closed as well as their source codes, which limits their use in scientific research. An alternative is the development of open source packages such as OpenFOAM, which makes it possible to not only to solve a wide range of tasks of continuum mechanics [4] with the use of standard solvers and utility, but also to improve them.

3. Features of numerical modelling of the unsteady vortex flows

Vortex flows generated by the various elements of an aircraft's structure can act on other stabilizing and control surfaces located in their wake, which causes aerodynamic buffet loads. In order to correctly simulate this phenomenon and to determine pulsating loads, it is necessary to properly calculate the process of propagation and dissipation of vortices. Thus, a criterion of correctness of the vortices' behavior description is Kolmogorov's energetic spectrum. Also for numerical simulation of vortex-breakdown it is necessary to use PISO algorithm and eddy-resolving approaches, for example LES and various hybrid methods combining RANS and LES models. However, an important feature of their application is that accuracy of the vortex flows calculation depends on the differencing schemes of convective flux discretization [5]. The necessary and sufficient condition for the differencing scheme is its stability and the ability to correctly describe dissipation of vortex flows. Therefore, selection of the optimal numerical scheme is one of the main tasks in simulation of vortex flows. On the one hand, the scheme should be low-dissipative i.e. generating the minimum of numerical diffusion and on the other hand, it should provide stable calculation and the absence of oscillations.

3.1. Analysis of numerical diffusionand stability of differencing schemes

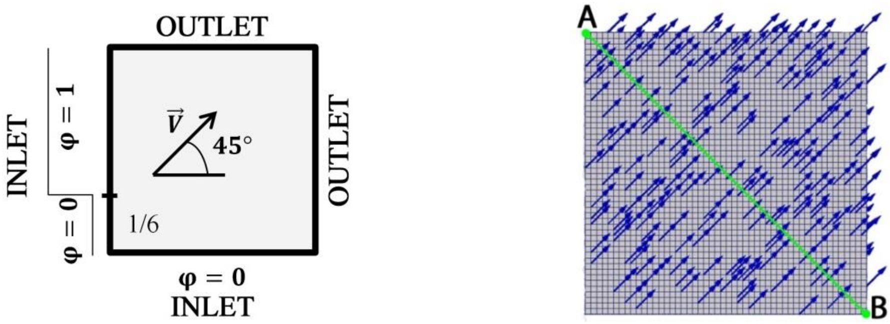
The analysis of related works has made it possible to isolate the differencing schemes for applied solutions implemented in OpenFOAM: 1st order upwind scheme (UD), central-differencing linear (CD) and SFCD schemes, blended and limited schemes like “blended”, QUICK, LUST, filteredLinear, Gamma and limitedLinear schemes. To investigate the quality of the selected schemes using the OpenFOAM package, two cases have been solved:

- Case of convective transfer of φ scalar with sharp gradients [6] which makes it possible to analyze schemes for stability.
- Case of decaying homogeneous isotropic turbulence [7] which allows for the evaluation of numericaldiffusion.

The problem of convective scalar transfer was solved in a two-dimensional installation with a square calculation area of 1 m^2 in which the scalar is transferred. Boundary and initial conditions are similar to work [6] and are shown in Figure 1. The computational grid consists of 30x30 cells uniformly distributed over the whole area. Stepped profile *φ(y)* is selected for vertical input boundary:

$$\varphi(y) = \begin{cases} 0 \; for \; 0 \le y < \dfrac{1}{6}, \\ 1 \; for \; \dfrac{1}{6} \le y \le 1. \end{cases}$$

Velocity equals to 5 m/s and is directed at a 45 degree angle to grid lines.



(a) (b)

Figure 1. Case of a scalar’s convective transfer: (a) step profile test set-up; (b) computational grid

Figure 2 shows a distinct view of φ field graphs along a diagonal line connecting lower right and upper left corners of the area’s geometry (Figure 1 (b), line AB).

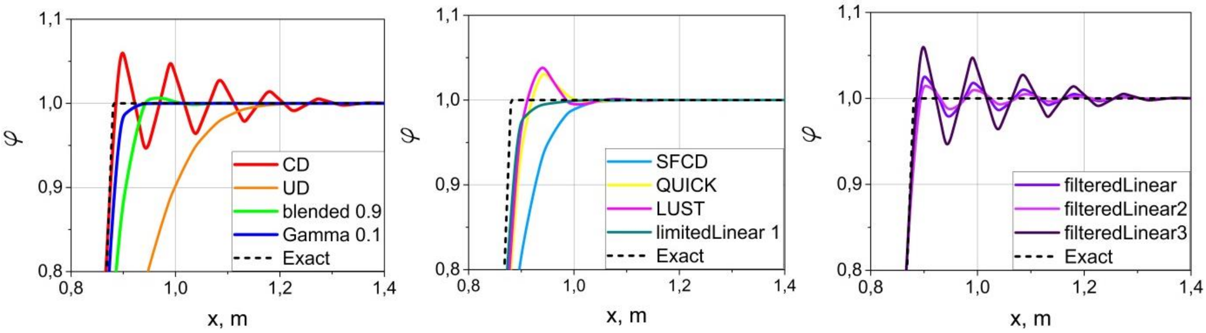
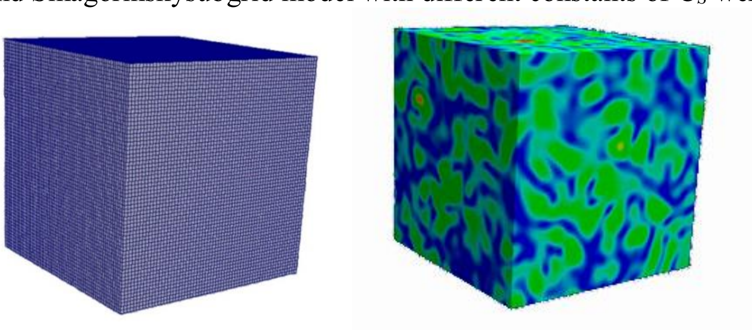


Figure 2. Convection of a step profile

It can be seen that the central-differencing scheme results in numerical oscillations and cannot be widely used in computational simulation of vortex-breakdown. The filteredLinear schemes also cause oscillations at any limiter value. The use of limited schemes, such as Gamma, or mixed schemes, such as blended with ratio of 0.9, eliminates numerical oscillations from the solution.

The differencing schemes should also properly describe the process of vortex dissipation when carrying out the calculations. For this purpose, the problem of decaying isotropic homogeneous turbulence has been solved. This problem helps to find out with high accuracy how dissipative is a certain convective flux discretization scheme [5]. Energy understating in different intervals of the energy spectrum indicates the numerical diffusion of the differencing scheme. This makes it possible to evaluate the suitability of each scheme for tests with the use of eddy-resolving approaches.

Numerical simulation of this task was carried out in a cubic design area with the size of 2π x 2π x 2π and a total number of cells 64^3 (Figure 3 (a)). The “cyclic” periodic boundary condition was used for all three spatial coordinates. Using boxTurb utilities included in the OpenFOAM package, an initial energy spectrum was set which generated a random field of speeds, used as initial condition (Figure 3 (b)). Then calculation was performed, after which the results were stored and transferred back to the energy spectrum which was compared to the experimental data [7]. For calculation, a method of large eddy simulation (LES) and Smagorinskysubgrid model with different constants of C_S were used.



(a) (b)

Figure 3. Case of decaying homogeneous isotropic turbulence: (a) grid; (b) initial speed field

Figure 4 presents the results of calculation with the aid of Smagorinskysubgrid model with a matched C_S constant. When the energy of the turbulent pulsations is reduced in the high-frequency region of the spectrum, the value of the constant C_S decreases and vice versa. In this way, the value of C_S was chosen so that the resulting energy spectrum matched the experimental one. It should be noted that in Smagorinsky model implemented in the OpenFOAM package the default values of $C_S = 0.167$. It can be seen that zeroing the constant C_S does not lead to correct mapping for following schemes: Gamma at $\gamma = 0.1$, SFCD, QUICK, limitedLinear. The least dissipative are central-differencing scheme (CD) at $C_S = 0.2$, schemes of the filteredLinear at $C_S = 0.167$ and blended with coefficient $\beta = 0.9$ at $C_S = 0.1$. These schemes can correctly describe the evolution of vortex structures by using eddy-resolving approaches.

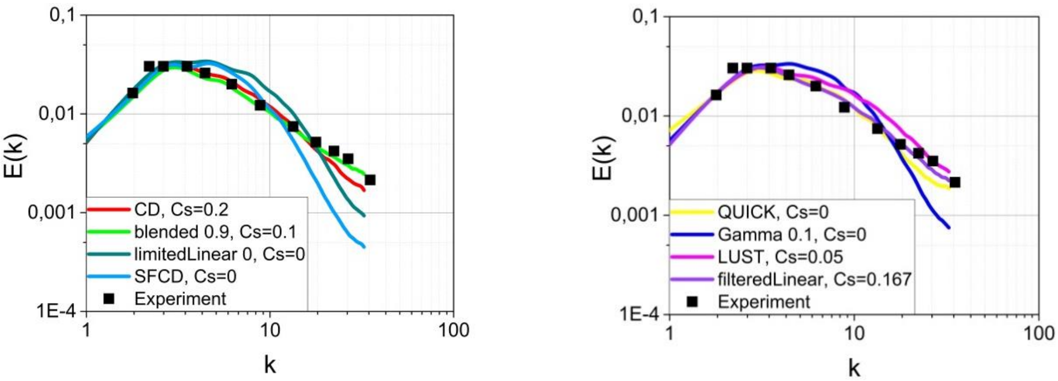


Figure 4. Energy spectra obtained with the aid of Smagorinsky model for various differencing schemes

Thus, the obtained results of the two cases solved allowed to carry out quality analysis of the differencing schemes for simulating the vortex flows which are implemented in the OpenFOAM software package. So, linear scheme correctly describes the evolution of vortex structures at $C_S = 0.2$, although it is unstable. Schemes of filteredLinear correctly map the energy spectrum with a small value understating in the high-frequency region, producing less oscillations than central-differencing scheme. The upwind scheme is stable but it is too dissipative. Use of "blended" scheme with ratio 0.9 makes it possible to increase its stability compared to CD, and at $C_S = 0.1$ it correctly describes the energy spectrum. However, understating viscosity by a factor of 2 leads to poor results in case of near-wall region. The QUICK and LUST schemes do not eliminate oscillation and are quite dissipative, since the correct description of the energy spectrum occurs at zeroing of the subnet viscosity, that is, at $C_S = 0$. Gamma, SFCD, and limitedLinear schemes are stable, but at any values of C_S they show understating of energy in the high-frequency region. It should also be noted that schemes such as upwind, SFCD, blended do not preserve the sharpness of the transfer edge like other schemes. Thus, the analysis of differencing schemes implemented in the OpenFOAM package shows that the schemes based on the central-differencing scheme are unstable and the upwind-differencing schemes are dissipative, therefore it is necessary to improve them in order to eliminate oscillations and maintain an acceptable level of numerical diffusion.

3.2. Modification of differencing schemes

Based on the results obtained above, differencing schemes filteredLinear and Gamma were selected and their improvement were carried out. Modification encompassed the adding of extra free parameters and changing the limiting coefficients in differencing schemes as well as determining their optimal values by solving the cases described above. This made it possible to change the behavior of the initial differencing schemes in the interval where the scheme's data was dissipative or unstable.

The basic idea of most numeric schemes implemented in the OpenFOAM package is that the weight coefficient is determined by each scheme independently and is essentially a function at software level (limiter) which returns its value from 0 to 1. At 0, the scheme is transformed into upwind, at 1 – in linear.

The Gamma scheme is implemented in the OpenFOAM package by the following function which determines weight coefficient:

$$\text{limiter} = \min\left(\max\left(\frac{\varphi_k}{\gamma}, 0\right), 1\right), \tag{3}$$

where $\varphi_k = 1 - (\varphi_N - \varphi_P) / \left(2\nabla\varphi_P \cdot \vec{d}\right)$ – face value; φ_N and φ_P – the solution of variables at points N and P (cell centers); $\vec{d}$ – vector connecting adjacent cell centers N and P; min and max are functions, which return the minimum and maximum values respectively. According to the equation (3) parameters on face are determined as follows:

$$\begin{cases} \varphi_k \le 0 - \text{limiter} = 0, \text{upwind is used;} \\ \varphi_k \ge 1 - \text{limiter} = 1, \text{linear is used;} \\ \gamma \le \varphi_k < 1 - \text{limiter} = 1, \text{linear is used;} \\ 0 < \varphi_k < \gamma - \text{limiter} = \dfrac{\varphi_k}{\gamma}, \text{blended is used.} \end{cases}$$

It can be seen that the implementation of this scheme is slightly different from the description in [7]. Below there is a modification of this scheme (named GammaM) carried out by adding additional free parameter δ to it, so that it does not become a UD scheme when going beyond the boundary of stability, which makes it possible to reduce its numerical diffusion:

$$\begin{cases} \varphi_k \le 0 - \text{limiter} = \delta, \text{blended is used;} \\ \varphi_k \ge 1 - \text{limiter} = 1, \text{linear is used;} \\ \gamma \le \varphi_k < 1 - \text{limiter} = 1, \text{linear is used;} \\ 0 < \varphi_k < \gamma - \text{limiter} = \dfrac{\varphi_k}{\gamma}, \text{blended is used.} \end{cases}$$

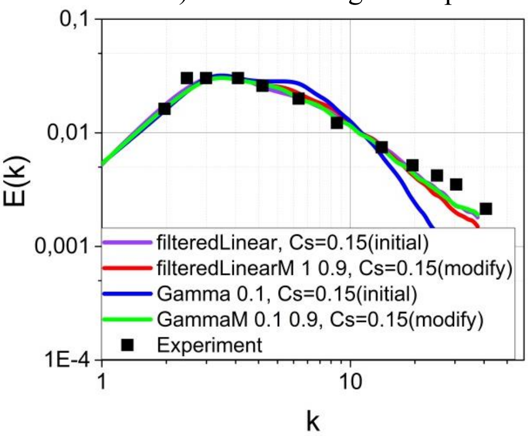
Presented below is filteredLinear scheme implemented in OpenFOAM package:

$$\begin{cases} f = 2 - 0.5\dfrac{\min\left(mag(\varphi_N - \varphi_P - \nabla\varphi_P d), mag(\varphi_N - \varphi_P - \nabla\varphi_N d)\right)}{\max\left(mag(\varphi_N - \varphi_P - \nabla\varphi_P d), mag(\varphi_N - \varphi_P - \nabla\varphi_N d)\right)} \\ \text{limiter} = \max\left(\min\left(f, 1\right), 0.8\right) \end{cases}$$

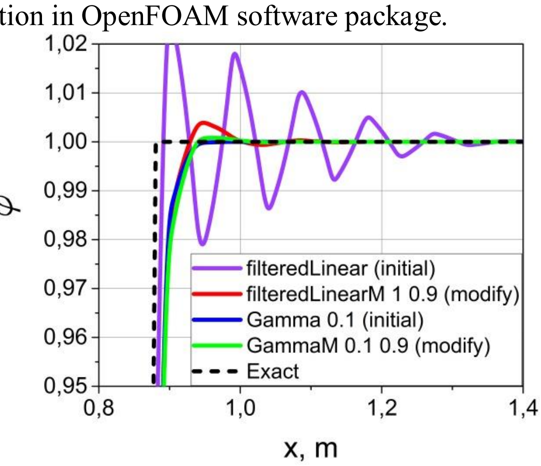
A modification of this scheme (named filteredLinearM) consists of including additional free parameters α and β and determining their optimal parameters for the purpose of decreasing oscillation:

$$\begin{cases} f = \alpha - 0.5\dfrac{\min\left(mag(\varphi_N - \varphi_P - \nabla\varphi_P d), mag(\varphi_N - \varphi_P - \nabla\varphi_N d)\right)}{\max\left(mag(\varphi_N - \varphi_P - \nabla\varphi_P d), mag(\varphi_N - \varphi_P - \nabla\varphi_N d)\right)} \\ \text{limiter} = \max\left(\min\left(f, 1\right), \beta\right) \end{cases}$$

The following is a study of the modified differencing schemes (GammaM and filteredLinearM), analysis of their free parameters and coefficients for stability and numerical diffusion, and their optimal values obtained by solving the two cases described above with the use of Smagorinsky model with constant $C_S = 0.15$. Figure 5 shows the comparison of modified differencing schemes (GammaM and filteredLinearM) with their original implementation in OpenFOAM software package.



(a)



(b)

Figure 5. Comparison of modified differencing schemes with their initial realization in OpenFOAM package: (a) energy spectrum; (b) convection of a step profile

Thus, differencing schemes based on the open source OpenFOAM package are proposed and implemented, optimal values of their free parameters and coefficients are determined (γ=0.1,δ=[0.8,0.9] for GammaM and α=1,β=[0.85,0.9] for filteredLinearM) which makes it possible to increase calculation accuracy of propagation and decaying processes for vortex flows. Some validation of the proposed schemes presented in [8].

3.3. Algorithm for combining various approaches for modeling turbulent flows

In case of calculating the flow around complex three-dimensional objects and real aircraft configurations RANS approach is not able to provide plausible accuracy, and LES requires large

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computational resources while the hybrid DDES method exhibits sufficient accuracy. However, this method imposes certain conditions on the quality of computational grid [9], the construction of which presents considerable difficulties and requires a large amount of time. A possible alternative is the use of zonal RANS-LES approach, the idea of which consists in using a resource-demanding LES approach in areas where accuracy of numerical simulation is to be increased, and RANS in the remaining zones of the computational domain.

Initial file analysis of OpenFOAM package shows that there is no prepared solution for using the zonal approach to determine aerodynamic characteristics. As a result, the algorithm based on combining RANS and LES approaches is proposed and implemented, which makes it possible to use combination of LES and RANS models in different regions of the computational grid. The key idea of this approach is that the majority of turbulence models in OpenFOAM return fields of turbulent viscosity τ and turbulence kinetic energy k as exit values. On the other hand, turbulence in the equation of momentum balance in the OpenFOAM is taken in through approximation of effective stress tensor, the numerical implementation of which is determined independently for each model.

The solution of the problem of combining RANS and LES approaches on software level implies the implementation of an algorithm that makes it possible to obtain common matrix of coefficients from two different models of turbulence, which will then be sent to the equation of momentum conservation in model. In this case, the problem of combining RANS and LES models includes three procedures:

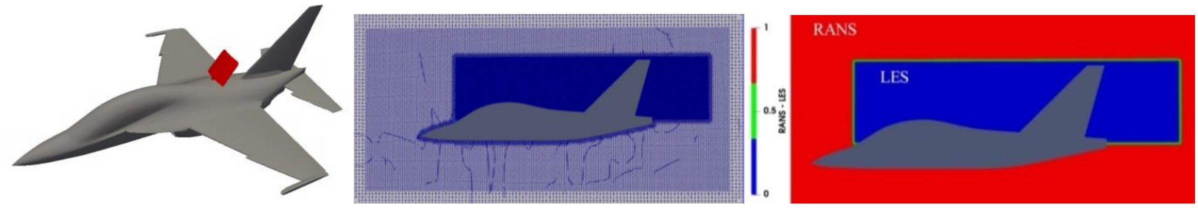
- determination of sub-areas of RANS and LES approaches' application based on flow patterns and study objectives;
- RANS model is used to calculate turbulent viscosity ν_{rans} and LES model is used for calculation of subgrid viscosity ν_{sgs};
- calculation of blended viscosity value ν_t as a function of ν_{rans} and ν_{sgs} using equation proposed J.Fröhlich and von D.Terzi [10].

In order to determine the sub-areas of use of RANS and LES approaches in the OpenFOAM package, a special ZoningArea utility is implemented, which analyzes the calculation grid created and stores the scalar data field in which each cell of the grid corresponds to one of the three values: 1 is the sub-area of RANS, 0.5 - mixed area, 0 - LES sub-area. This field is the initial condition for carrying out numerical calculation. It is worth noting that for RANS approach, in general, stable upwind-differencing schemes are used which are too dissipative for LES. In turn, low dissipative schemes are used for LES, which may be unstable in RANS domain. This fact has also been taken into consideration when implementing this algorithm, which makes it possible to use different numerical schemes for each of the approaches.

The implemented zonal approach combining RANS and LES models allows to carry out numerical modelling of unsteady vortex flows around of aircraft using the open-source utilities of OpenFOAM which increases the accuracy of aerodynamics characteristics determination.

4. Numerical simulation flow around an aircraft considering airbrake

A series of calculations of three-dimensional flow around a maneuverable aircraft using the modified differencing schemes and algorithm described above was carried out. The effect of the airbrake release on the dynamic loads on the tail fin was investigated. The solution was found with the following initial data: velocity of the incoming flow V_∞ = 50 m/s, kinematic viscosity $\nu = 1.5\cdot10^{-5}$m^2/s, Reynolds number $Re = 6\cdot10^5$. Calculation time step was chosen by condition CFL ≤ 0.2. Field of RANS and LES models' use was set by the initial conditions. In this case, it was necessary to accurately model the breakdown of vortices from the canopy and the airbrake of the aircraft at different angles of attack. Therefore, flow in the rest of the region could be obtained by means of RANS model. As RANS model of turbulence, k-ω SST was used, whereas for LES model it was Smagorinsky model with constant $C_S = 0.15$. Figure 6 shows the aircraft design and a grid fragment with cell number equal to 15 million. All calculations were carried out using the equipment of the shared research facilities of HPC computing resources at Lomonosov Moscow State University.



(a) (b) (c)

Figure 6. Case setup of the flow around an aircraft with a airbrake: (a) aircraft design; (b) section of computational grid; (c) field of application for RANS and LES approaches

In Figure 7 and Figure 8 the aerodynamics characteristics of the aircraft with and without the airbrake are presented and compared to experimental data [11].

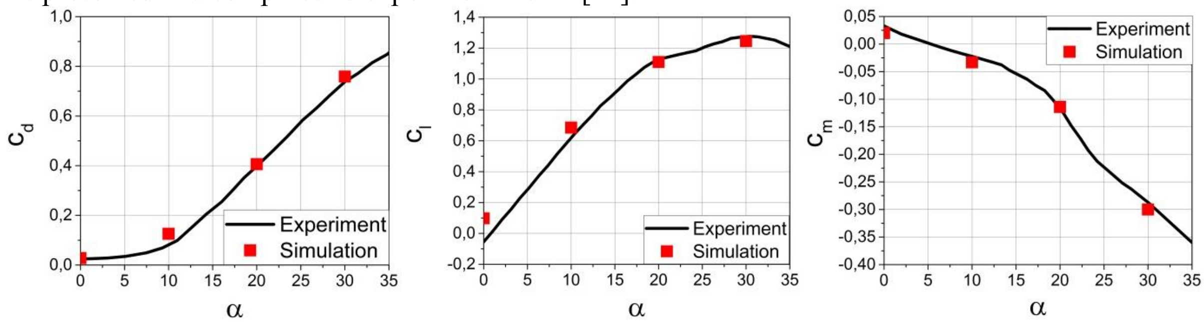
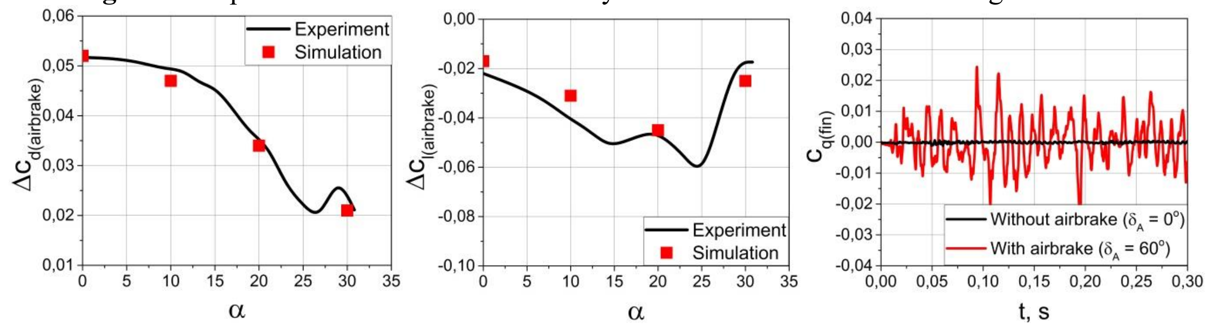


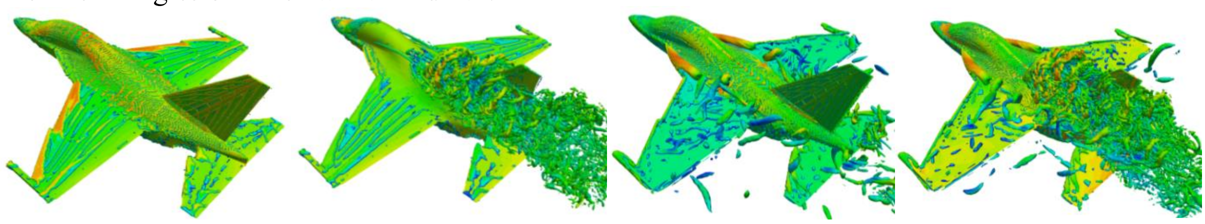
Figure 7. Dependence of the aircraft's aerodynamics characteristics on the angle of attack



(a) (b) (c)

Figure 8. The influence of the airbrake release on the change of aerodynamic coefficients: (a) drag; (b) lift; (c) lateral force on the tail fin (α= 0°)

It can be seen that the results of numerical simulation using the proposed technique are consistent with experimental data, and the occurrence of aerodynamic buffet loads is confirmed at the airbrake deflection angle of δ_A = 60°. Figure 9 shows flow structures around the aircraft with and without the airbrake at angles of attack α = 0° and 20°.



(a) (b)

Figure 9. Instantaneous vortex structures (iso-surface of Q-criterion) of flow around an aircraft with and without airbrake at angles of attack: (a) α = 0°; (b) α= 20°

5. Conclusion

A technique is proposed for calculating the aerodynamic characteristics of a maneuverable aircraft and its control elements with the use of an improved open source OpenFOAM package, which makes it possible to model the vortex flow around its stabilizing and control surfaces by a subsonic incompressible flow with sufficient accuracy. This makes it possible to carry out the detailed analysis of the processes of aerodynamic buffet loads occurrence at early stages of aircraft design. Implementation of the algorithm for combining RANS and LES approaches and differencing schemes makes it possible to increase reliability of an aircraft's aerodynamic characteristics with the account of the vortex flows. The technique was confirmed by comparison with experimental data.

Modification and improvement of open source OpenFOAM package has been carried out, which makes it possible to use it for research and evaluation of parameters of unsteady vortex flows, and also calculation of force loads on the elements of the aircraft when solving a wide range of scientific tasks in the aircraft industry.

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