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Numerical simulation and stability analysis of wall-bounded turbulent flows

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ABSTRACT

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Thesis can be found in the library and on the website http://www.spbstu.ru/science/ of Peter the Great St. Petersburg Polytechnic University

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Scientific secretary of
the Dissertation Committee U.01.02.05
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General description of the work

The dissertation outlines the main results of the author's nearly twenty-year work in the area of numerical computations of wall-bounded turbulent flows. In particular, it describes the mathematical models of different levels of completeness developed by author and presents the results of systematic numerical studies of a wide range of wall-bounded flows performed using the models, which are of great methodological and practical interest. Along with this, the dissertation presents a set of pioneering studies devoted to a linear analysis of the stability of steady RANS solutions, including both the development of appropriate methods and computational algorithms, and their application to determine the conditions of transonic buffet onset on wings.

The relevance of the research topic and the extent of its development

The problem of modeling turbulent flows is one of the few unresolved problems of computational fluid dynamics, on which a huge number of researchers all over the world continue to work. As a result, serious advancements have been made in this area, consisting of both a significant improvement of the existing semi-empirical models and the creation of new, more precise and informative approaches to the description of turbulent flows. However, a “conclusive” solution to this problem, being the creation of a tool that provides an accurate computation of all the properties of turbulent flows of any complexity level, can only be achieved in the frame of Direct Numerical Simulation (*DNS*) of turbulence. According to even the most optimistic predictions, this will become possible only in the XXII century. Taking into account this fact and the urgent need of many key industries for reliable data on the characteristics of a wide range of turbulent flows, the problem of increasing the accuracy of their prediction will remain one of the most relevant and important problems of theoretical and computational fluid dynamics. The results presented in the dissertation are devoted to solution of this complex and important task.

Goals and objectives of the work

The main goal of the work is the improvement of the methods of wall-bounded turbulent flows modeling and the application of the developed methods to calculations of such flows.

The specific tasks that are solved in the dissertation to achieve these goals are:

- conducting an analytical review of existing methods of numerical simulation of wall-bounded turbulent flows and determining possible ways for their further improvement;
- expanding the limits of the applicability and increasing the reliability of the best existing semi-empirical turbulence models for Reynolds Averaged Navier-Stokes (*RANS*) equations closure;

- improvement of global hybrid scale-resolving RANS – LES approaches based on the two-equation *k*-ω SST model;
- development of technological algorithms for the implementation of zonal RANS – LES approaches compatible with unstructured grids;
- comprehensive testing of the developed models and methods based on a comparison of the obtained results with existing experimental data and the results of direct numerical simulation;
- application of hybrid RANS – LES approaches to simulation of a number of complex wall-bounded turbulent flows of practical use;
- development of a methodology and construction of algorithms for a linear stability analysis of stationary solutions of the RANS equations, their verification, testing and application to predicting the transonic buffet onset on wings.

Scientific novelty

1. A number of original modifications of the two most successful semi-empirical turbulence models for calculating near-wall turbulent flows have been developed, namely, the Spalart-Allmaras eddy-viscosity model (SA model) and the two-equation *k*-ω SST of Menter (SST model). In particular, it was proposed:
   - two nonlinear models (BSL EARSM and SST NL models), designed to improve the accuracy of computation of flows with essential Reynolds stress anisotropy;
   - a new correction to take into account the effects of streamline curvature and flow rotation for the SST model (SST RC1 model);
   - a modification of the SST model, which provides increased accuracy in calculating the flow around airfoils at stall conditions (SST HL model);
   - two modifications of the SA model, improving the accuracy of computation of axisymmetric flows (SA TC model) and boundary layers at low local Reynolds number (SA Low-Re model).
2. Significant improvements of existing hybrid scale-resolving RANS-LES approaches have been proposed, namely:
   - two versions of well-known global (non-zonal) methods DDES and IDDES based on the SST model, one of which improves protection of attached boundary layer from unwanted activation of the LES mode, and the other allows to significantly simplify the model formulation without loss of accuracy;
   - adaptation of two efficient methods for the acceleration of transition to developed turbulence in the detached mixing layers designed for the SA model to hybrid RANS-LES approaches based on the SST model;
   - an efficient technology for implementing the one-stage zonal RANS-LES approach using volume sources in the momentum and kinetic energy transport equations to generate

turbulent content on the RANS-LES interface, applicable on arbitrary (both structured and unstructured) grids.

3. A new hybrid finite-volume scheme for inviscid flux approximation for the global hybrid RANS-LES approaches has been developed. The scheme ensuring stability of the algorithm and high accuracy of resolution of turbulent structures in attached and separated wall-bounded flows.
4. New data on aerodynamic and aero-acoustic characteristics of a number of complex wall-bounded flows have been obtained using hybrid scale-resolving RANS-LES approaches. In particular, the following flows have been considered:
   - tandem cylinder flow;
   - flow around DLR-F15 high-lift airfoil;
   - flow around the wing-flap model configuration;
   - trans- and supersonic flow around the reentry vehicle and the detachable head unit of the manned transport ship in take-off mode and during emergency separation from the launch vehicle.
5. A new zonal RANS-DNS-IDDES approach has been developed and used for simulation of transonic flow over a bump on the cylindrical surface, characterized by shock-boundary layer interaction accompanied by separation and attachment of the flow on the unprecedented for Russia computational grid of 8.3 billion nodes.
6. A new approach to the global stability analysis of the turbulent flows based on the linear stability analysis of steady RANS solutions has been proposed and corresponding economical methodology and numerical algorithms are developed. Developed approach has then been used for the identification of the conditions of transonic buffet onset on the straight and swept wings of infinite span.

Theoretical and practical significance of the work

The theoretical significance of the work consists in:

- the development of new RANS turbulence models and hybrid RANS-LES approaches;
- the study of patterns of a number of turbulent flows of considerable theoretical interest;
- the development of a new approach to the analysis of global stability of turbulent flows and the appropriate methodology for carrying out a linear stability analysis of steady solutions of the RANS equations.

The practical significance of the work consists in:

- increasing the accuracy of computations of different important practical applications within the framework of the RANS equations;
- simplifying and increasing the accuracy of the hybrid DDES and IDDES models based on the SST model;

- the development of a new hybrid scheme for the inviscid flux approximation, which provides an increase in the accuracy of simulations within the framework of global hybrid RANS-LES approaches;
- obtaining detailed calculation data on unsteady aero-acoustic loads on the elements of a manned spacecraft during flight in the dense layers of the atmosphere;
- creating an effective methodology for determining the conditions of the transonic buffet onset on wings and in obtaining the corresponding calculated data for various airfoil shapes.

Methodology and research methods

The dissertation uses the now-classic methodology for numerical modeling of turbulent flows, based on semi-empirical and statistical theories of turbulence and on methods of numerical integration of systems of partial differential equations expressing the general laws of conservation of mass, momentum and energy in turbulent fluid flows.

The academic finite-volume CFD code “Numerical Turbulence Simulation” (NTS code) is used as the main computing tool. This code has been successfully used for almost three decades to calculate turbulent flows within the framework of RANS, LES, DNS, and hybrid RANS-LES approaches and has been carefully verified by comparison with known analytical solutions and with the results of numerical calculations obtained using other CFD well-known codes (ANSYS FLUENT and ANSYS CFX, DLR TAU, NOISEtte, SINF, etc.).

Finally, the methods of the classical linear theory of stability are used to analyze the stability of stationary solutions of the RANS equations. The eigenvalues and eigenvectors of the linear differential operator are calculated numerically with discretization on the same computational grid as the solution being studied.

The main results to be defended

1. Modifications of the best known semi-empirical turbulence models, providing an increase in their accuracy and/or expanding the boundaries of their applicability:
   - two nonlinear models for computations of flows with essential Reynolds stress anisotropy (BSL EARSM and SST NL models);
   - two modifications of the linear SST model, which provide an increase in the accuracy of predictions of flows around airfoils at stall conditions (SST HL model), as well as flows with significant influence of streamline curvature and rotation (SST RC1 model);
   - two modifications of the SA model to improve the accuracy of calculating axisymmetric flows (SA TC model) and attached boundary layers at low Reynolds numbers (SA Low Re model).
2. New formulations of global hybrid RANS-LES models DDES and IDDES based on the SST model:

  - simplification of formulations and elimination of the possibility of activating the LES mode in the attached boundary layers;
  - new non-zonal hybrid RANS-LES model SST σ-DDES, providing significant acceleration of formation of the resolved turbulent structures in the detached mixing layers.
3. Technology of implementation of zonal hybrid RANS- LES approaches, which is suitable to use on arbitrary grids, structured and unstructured.
4. A new hybrid numerical scheme providing stability and low dissipation of the computational algorithm in the framework of global hybrid RANS-LES approaches.
5. New quantitative data on the aerodynamic and aero-acoustic characteristics of a number of complex wall-bounded turbulent flows obtained using hybrid RANS-LES approaches:
  - tandem cylinder flow;
  - flow around DLR-F15 high-lift airfoil;
  - flow around the wing-flap model configuration;
  - trans- and supersonic flow around the reentry vehicle and the detachable head unit of the manned transport ship.
6. A new approach to the analysis of global stability of turbulent flows based on a linear stability analysis of stationary solutions of the RANS equations, the corresponding methodology and computational algorithms that implement this approach, as well as the results of their application to determine the transonic buffet onset conditions on the straight and swept wings.

Reliability and approbation of the results.

The reliability of the results obtained in the dissertation is ensured by:

- the use of mathematical models based on fundamental fluid mechanics laws;
- verification of the absence of significant dependence of the obtained solutions on the computational grid, the integration time step (for unsteady flows) and the size of the computational domain, which guarantees the absence of significant computational errors;
- good agreement between the results obtained in the dissertation using the NTS code and the ANSYS FLUENT code, which has been independently verified in a huge number of studies;
- a detailed physical analysis of the results, as well as comparing these results with experimental data and direct numerical simulation results known from the literature.

Approbation of the results. Main work results were reported on the following Russian and international conferences, seminars, and workshops:

1. European Conference for Aeronautics and Space Sciences EUCASS (2005, 2009, 2011).
2. International symposium “Global Flow Instability and Control” (Crete, Greece, 2005, 2009).

3. International Symposium on Hybrid RANS-LES Methods HRLM (2005, 2009, 2011, 2014).
4. School-seminar of young scientists and specialists under the guidance of academician A.I. Leontiev (Russia, 2005, 2011, 2013, 2015, 2017).
5. 60th Annual Meeting of the Division of Fluid Dynamics (Salt Lake City, USA, 2007).
6. IUTAM symposium on Unsteady Separated Flows and their Control (Corfu, Greece, 2007).
7. In-chamber processes and combustion in solid fuel and barrel systems ICOC (Saint-Petersburg, Russia, 2008).
8. AIAA Theoretical Fluid Mechanics Conference (USA, 2008, 2011).
9. Workshop on Quality and Reliability of Large-Eddy Simulations II (Pisa, Italy, 2009).
10. International conference “Computational Experiment in Aeroacoustics” (Svetlogorsk, Russia, 2010, 2014, 2016, 2018).
11. AIAA-NASA Workshop on Benchmark Problems for Airframe Noise Computations - I BANC-I (Stockholm, Sweden, 2010).
12. Workshop CFD for Nuclear Reactor Safety Applications CFD4NRS-4, (Daejeon, South Korea, 2012).
13. Video workshop on aeromechanics TsAGI - ITAM SB RAS - SPbPU - NIIM Moscow State University (St. Petersburg, Russia, 2012, 2017).
14. International Symposium on Turbulence and Shear Flow Phenomena TSFP8 (Osaka, Japan, 2013).
15. International Conference PhysicA.SPb (Saint-Petersburg, Russia, 2013, 2015, 2016, 2017).
16. European Conference on Computational Fluid Dynamics ECFD VI (Barcelona, Spain, 2014).
17. Russian National Conference on Heat Transfer RNKT (Moscow, Russia, 2014, 2018).
18. International ERCOFTAC Symposium on Engineering Turbulence Modelling and Measurements ETMM (2014, 2016).
19. 7th European Congress on Computational Methods in Applied Sciences and Engineering, ECCOMAS (Crete, Greece, 2016).
20. International conference “Russian Supercomputing days” (Moscow, Russia, 2016).
21. International Conference "Modern Problems of Thermophysics and Energy" (Moscow, Russia, 2017).
22. AIAA Fluid Dynamics Conference (Atlanta, USA, 2018).
23. XXV All-Russian Seminar with International Participation in Inkjet, Separate, and Unsteady Flows (St. Petersburg, Russia, 2018).

The author’s publications and contribution

Materials of the dissertation were published in 62 papers, 18 of which are included in the HAC List, and 39 in one of the Web of Science and/or Scopus databases.

The results to be defended, the simulation results and their analysis belong to the author personally or were obtained with his decisive participation. All simulations presented in the dissertation, with the exception of the case explicitly indicated in section 2.3.1.5, were made by the author or under his direct supervision.

Structure and scope of work

The dissertation consists of an introduction, five chapters and conclusion. Total volume of dissertation is 284 pages, including 269 figures and 20 tables with 435 references.

The main content of the work

The **introduction** substantiates the relevance of the topic of the dissertation and analyzes the main development trends and the current state of research in the field of modeling and simulation of wall-bounded turbulent flows. This analysis allows to specify the position of the studies presented in the dissertation in the general series of works devoted to solving this problem. At the end of the introduction, the structure of the dissertation and the content of its individual chapters are briefly described.

Chapter 1 presents an analytical review of existing at the beginning of the study (2000s years) approaches to modeling and simulation of wall-bounded turbulent flows, consisting of two sections. The first of them (**Section 1.1**) considers semi-empirical turbulence models for the closure of the RANS equations, and the second (**Section 1.2**), hybrid scale-resolving methods (Hybrid RANS-LES models or HRLM) based on the joint use of RANS models and the Large-Eddy Simulation (LES) method.

For many years, RANS models have been and still remain the main tool for simulation turbulent flows at high (of practical use) Reynolds numbers. Therefore, a huge number of studies have been devoted to their construction and application, conducted both by individual scientists and scientific groups, and as part of large international programs. As a result, an extremely wide range of more or less successful models of this type was developed in the 20th century. However, their widespread use and careful testing, which became possible due to the rapid development of computer technology, shows that all these models are only applicable for a limited range of relatively simple flows (it is discussed in detail in section 1.1). Thus, by the end of the 20th century, consensus was reached on the impossibility of creating a universal RANS model of turbulence, which redirected the main efforts of researchers from attempting to build such a model to improving the best of the known models

The second characteristic feature of the period under consideration, which influenced the development of RANS models, was the steady increase in the share of applied calculations carried out using commercial CFD codes developed mainly for engineers and designers. In this regard, the requirements for the computational reliability of models have increased significantly, i.e. to the possibility to obtain converged steady RANS solutions automatically (without "manually" selecting relaxation parameters of the corresponding iterative procedures) on strongly non-isotopic structured and unstructured grids used in the calculation of flows with complex geometry. This circumstance was taken into account when developing the advanced RANS models presented in Chapter 2 of the dissertation.

In section 1.2 of the review two most representative groups of hybrid scale-resolving RANS-LES models are considered in detail, namely global (non-zonal) HRLM (**section 1.2.1**), and zonal HRLM, based on an a priori dividing of the whole computational domain into RANS and LES subdomains (**section 1.2.2**). Both types of models combine the best qualities of RANS and LES approaches in various ways and are now regarded as the only real alternative to RANS models for simulation of the complex separated turbulent flows at high Reynolds numbers of practical interest.

Based on the analysis of the models of the first group, it was concluded that the so-called "DES-like models" (models built on the basis of the Detached Eddy Simulation or DES method proposed in 1997) have the highest potential among them. The most widespread among such models were the Delayed DES (DDES) and Improved DDES (IDDES) approaches, which eliminated some of the important shortcomings of the original version of the DES method that were identified as a result of its widespread use that began in the first years of XXI century. The most advanced formulations of DDES and IDDES are based on a new ("shear-layer adapted") definition of the subgrid linear scale, which depends not only on the steps of the computational grid, but also on the local kinematic characteristics of the flow. Using this scale allowed to solve one of the most complex problems in the field of DES-like HRLMs, which consists in delaying the formation of developed three-dimensional turbulence in the detached mixing layers (one of the examples of so-called "gray area" problem). However, these formulations are based on the SA model, which, as is known, leads to a delay in the flow separation under adverse pressure gradient, which, in turn, entails a significant decrease in the calculation accuracy as a whole. Therefore, the development of similar HRLMs based on other RANS models providing a more accurate prediction of the separation point/line is of great practical interest. The main efforts of the author in the field of improving DES-like HRLMs were directed for solving this problem.

In frame of second HRLM group, discussed in Section 1.2.2, the computationally expensive LES method is used only in areas of the flow that obviously cannot be satisfactorily described in the framework of RANS or where it is necessary to obtain information on the actual instantaneous characteristics of turbulence (for example, aero-acoustic and aero-elasticity problems) unavailable in RANS. The models of this group are more flexible than global DES-like methods, however their use requires to take non-trivial decisions regarding the configuration of the RANS and LES subdomains of the computational area. In contrast to DES-like HRLMs, within zonal HRLMs, the problem of "cross-linking" solutions at the boundaries of different subdomains takes place. In this regard, the most difficult situation is when the flow is directed from the RANS subdomain to the downstream LES subdomain. This problem is caused by the fundamentally different ways the turbulence is described in the RANS and LES frameworks. In the RANS subdomain, all turbulent structures are modeled and the solution contains information only about the averaged flow characteristics and some statistical turbulence parameters. In order to provide a quick transition to LES, in which the main part of the turbulent vortex structures is resolved, it is necessary to create artificial (synthetic) turbulence at the input boundary of the LES subdomain, namely, to specify transient fluctuations of flow variables. Otherwise, LES subdomain will contain an extended transition zone in which the calculation accuracy is significantly reduced. This can be done only using some approximate assumptions about the spatiotemporal structure of turbulence in the vicinity of the RANS-LES interface, the validity of which determines the duration of relaxation of artificially created fluctuations to “true” turbulence, i.e., the length of the transition zone.

Along with the noted fundamental problem, there are some serious technological difficulties to the implementation of the RANS- LES interface conditions, because they rely significantly on the features of the computational code used (type of computational grid and method of data storage). As a result, the RANS and LES joining methods specific to one computational code can turn out to either be inapplicable in other codes or require significant adaptation.

An analysis of the works devoted to solving this problem (Section 1.2.2) showed that one of the most effective methods for generating synthetic turbulence is the so-called “artificial forcing” in the buffer zone introduced between the RANS and LES subdomains. In this zone, unsteady volume sources (VS) and/or sinks are introduced into the equations of momentum transfer and kinetic energy of turbulence. They are designed to ensure the matching of the statistical characteristics of the turbulence (components of the Reynolds stress tensor) at the exit from the buffer zone with the corresponding RANS characteristics at the exit from the RANS subdomain. The main advantage of this approach is that when using RANS-LES, the interface is not “attached” to the computational grid (it may not coincide with any grid surface), which is fundamentally important when using unstructured grids. However, the transmission of information on the statistical parameters of turbulence from the RANS subdomain to the buffer zone is an independent complex task, one of the solutions of which is proposed in Section 3.1.3 of Chapter 3.

Chapter 2 presents the new results obtained in the area of improving RANS turbulence models. It provides the mathematical formulations of developed models (**Section 2.1**), the numerical methods used for their implementation (**Section 2.2**), and the results of their verification and testing (**Section 2.3**).

The first two of the proposed modifications of the RANS models (BSL EARSM model and non-linear version of the k-ω SST model, the SST NL model) are intended to increase the accuracy of the computation of flows in which the anisotropy of Reynolds stresses plays a significant role. These, in particular, include flows in dihedral angles such as in the area of wing – body junction, at the root of turbine blades, in channels of rectangular cross-section, etc. The third modification of the k-ω SST model (SST RC1 model) expands the range of its applicability for flows, in which the effect on the streamlines curvature and flow rotation significantly affects the turbulence (flows in curved channels, vortex traces, etc.). The fourth model (SST

HL) provides a substantial increase in its accuracy when calculating the flow around airfoils at stall conditions (at angles of attack providing the highest aerodynamic lift).

Along with this, two modifications are proposed that extend the applicability of the SA model, which, like the SST model, is widely used in solving aerodynamic problems. The first of them (SA TC model) provides a significant increase in the accuracy of the original version of the SA model when calculating axisymmetric flows (for example, a submerged round jet), and the second (SA-Low-Re model) when calculating flows in the attached boundary layers at relatively low local Reynolds numbers, which is important for some applications.

The proposed models were implemented in two CFD codes: the NTS (Numerical Turbulence Simulation) code of the Laboratory for Computational Aeroacoustics and Turbulence of SPbPU and in the general purpose code ANSYS FLUENT (in the form of User Defined Functions - UDF). Some details of these codes in relation to RANS computations are also presented in **Section 2.2**.

A comparison of the results of computations of a number of flows obtained using both codes showed that they practically coincide. Taking into account a fundamental difference between these codes, the results coinciding is convincing evidence of the correctness of the software implementation of the developed models. Other than that, the BSL EARSM model was independently implemented by the developers of the ANSYS CFX[1], NUMECA[2] and TsAGI[3] codes based on the published version of this model. Results obtained by these researchers were compared with the author's published results, obtained using the NTS code, and in all cases their proximity was ascertained.

Testing of the developed models (**section 2.3** of the dissertation) was carried out in two stages. The first of them checked whether the proposed improvements of basic SST and SA models lead to an unforeseen decrease in the accuracy of prediction the canonical turbulent wall-bounded flows properties on which they were calibrated. At the second (main) stage, more than twenty turbulent flows of different complexity levels were calculated, for which the developed models should provide higher accuracy than the corresponding basic models. The obtained results were compared with the experimental data and DNS results available in the literature, and with the results obtained by the author using the original versions of the SST and SA models. Some examples of these comparisons are presented in Fig. 1 - Fig. 6, clearly show the significant advantages of the modified models. It should be noted that all the proposed modifications do not decrease the speed of convergence to the stationary solution and do not lead to any noticeable increase in the calculation time compared to the basic models.

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[1] Menter F.R., Garbaruk A.V., Egorov Y. Explicit Algebraic Reynolds Stress Models for Anisotropic Wall-Bounded Flows // EUCASS – 3rd European Conference for Aero-Space Sciences. 2009.

[2] Mehdizadeh O.Z., Temmerman L., Tartinville B., Hirsch C. Applications of EARSM turbulence models to internal flows // Proceedings of ASME Turbo Expo 2012 GT2012-68886. 2012.

[3] Troshin A.I., Vlasenko V.V., Wolkov A.V. Implementation of EARSM turbulence model within discontinious Galerkin method // 29 Congress of the International Council of the Aeronautical Sciences. 2014.

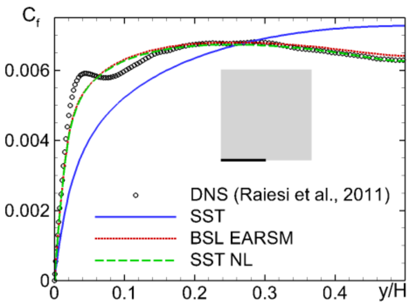

Fig. 1. Comparison of the friction coefficient distributions along the square channel wall computed using the proposed models with results of the SST model and DNS.

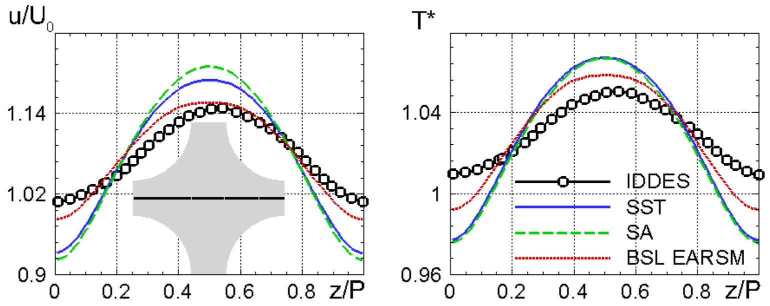

Fig. 2. Comparison of the velocity and temperature profiles in the central section of the inter-rod channel calculated using the proposed BSL EARSM model, with the SA and SST solutions and with the results of IDDES performed in this work.

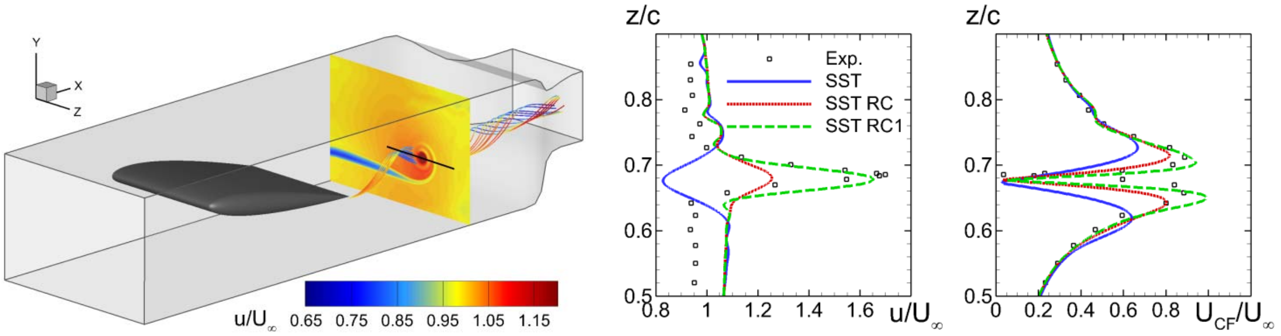

Fig. 3. The velocity field in the tip vortex obtained using the proposed SST RC1 model (left) and comparing the profiles of the streamwise and circumferential velocity components at a distance of 0.68c from the trailing edge of the wing, obtained using this model, SST, and SST RC[4] models, with experimental data from Chow et al., 1997.

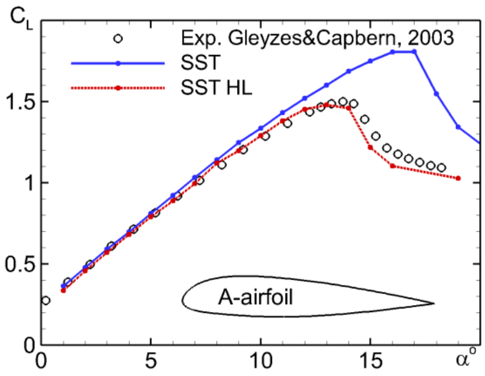

Fig. 4. Comparison of the dependences of the lift coefficient on the angle of attack for the A-airfoil calculated using the proposed SST HL and the basic SST models with experimental data.

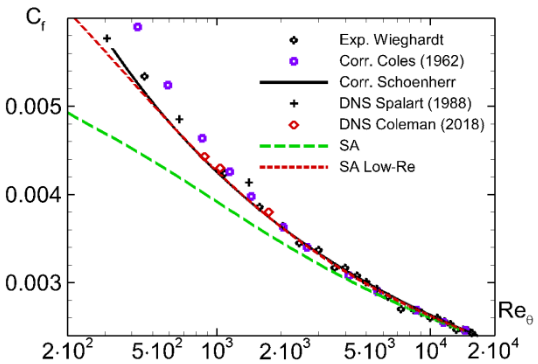

Fig. 5. Comparison of the skin friction coefficient distribution on a flat plate obtained using the proposed SA Low-Re and the basic SA models, with experiment, experimental correlations, and DNS results.

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[4] Smirnov P.E., Menter F.R. Sensitization of the SST Turbulence Model to Rotation and Curvature by Applying the Spalart–Shur Correction Term // Journal of Turbomachinery, Vol. 131, 2009. P. 041010.

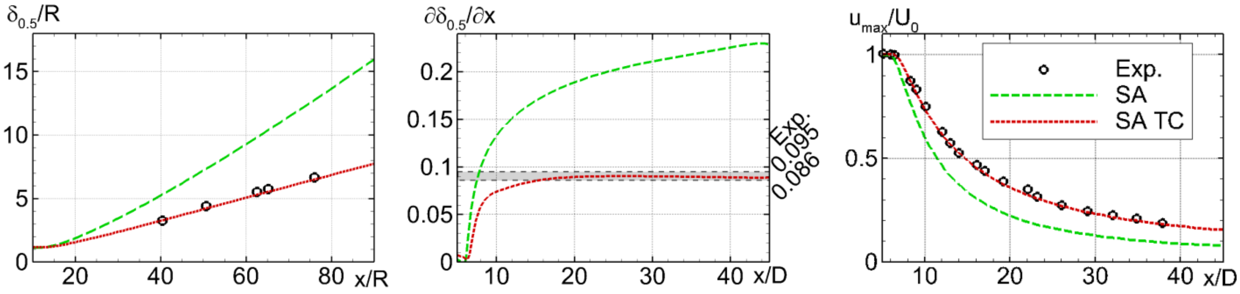

Fig. 6. Comparison of the results of submerged round jet computations obtained using the proposed SA TC and the SA base models with experimental data from Albertson et al., 1948.

Chapter 3 presents the results of the author's research in the development of hybrid RANS-LES approaches to turbulence modeling. Its first section (**section 3.1**), consists of the mathematical formulations of models of this type proposed in the dissertation, in **section 3.2** the numerical methods used for the models' implementations are described, and in **section 3.3** the results of testing of the models are presented.

In particular, in **section 3.1.1**, an updated formulations of the original versions of DDES and IDDES are described, in which the empirical constant C_{d1} is recalibrated as applied to the basic SST model (in the original versions of DDES and IDDES, this calibration was performed for the basic SA model and the obtained constant value is $C_{d1} = 8$). The significant positive effect of the proposed change of this constant (the effectiveness of preventing the activation of the LES mode in the attached boundary layers depends on it) is clearly illustrated in Fig. 7. The figure illustrates that when using the recalibrated value of $C_{d1} = 20$, the deviation between the skin friction coefficient distributions along a flat plate obtained using SST DDES and SST RANS starts at a much higher local Reynolds number than with $C_{d1} = 8$, and the deviation itself becomes much smaller.

The second modification of the SST IDDES model, described in the same section, consists in its significant simplification without any noticeable decrease in accuracy.

Section 3.1.2 presents new (adapted to the SST model) formulations of the two most effective methods for accelerating the transition to developed three-dimensional turbulence in detached mixing layers in the framework of DES-like HRLMs (SST version of the σ-DDES and SST DDES model in combination with the shear layer adapted subgrid scale Δ_{SLA}).

Finally, **Section 3.1.3** describes a technology that opens up the possibility of implementing zonal HRLMs not only on structured, but also on unstructured computational grids. The technology is based on the generation of artificial turbulence at the entrance to the LES subdomain of the computational domain by adding volumetric unsteady sources (VS) to the momentum and turbulent kinetic energy transfer equations. A key element of this technology is the use of a hybrid algebraic model in the VS zone, which opens a possibility to use the transport equations for the statistical turbulent characteristics k and ω to specify the scales of artificial turbulence generated in this zone.

Section 3.2 presents a new scheme for the inviscid flux approximations in the momentum and energy transfer equations in the framework of global HRLMs, which was developed as the part of the dissertation work and implemented in the NTS code. The main difference between this scheme and the commonly used family of schemes based on the idea of weighing low-dissipative central-difference and highly stable upwind schemes with a weight function, which ensures the predominance of a central-difference scheme in the LES area and an upwind scheme in the RANS area, is as follows. Instead of a purely upwind scheme, it uses the bounded central differencing (BCD) scheme, which itself is weighted and is used in some CFD codes, including ANSYS Fluent, for carrying out calculations within the framework of global HRLMs. As a result (Fig. 8), the final scheme detailed description of which is given in the dissertation automatically ensures the predominance of the BCD scheme in the areas of the flow where the RANS HRLM mode is active (attached boundary layers in the absence of turbulent content) and in the external inviscid flow. At the same time, in the attached boundary layers in the presence of turbulent content and in the separation zones and detached mixing layers (including their initial part), the low-dissipative central-difference scheme prevails.

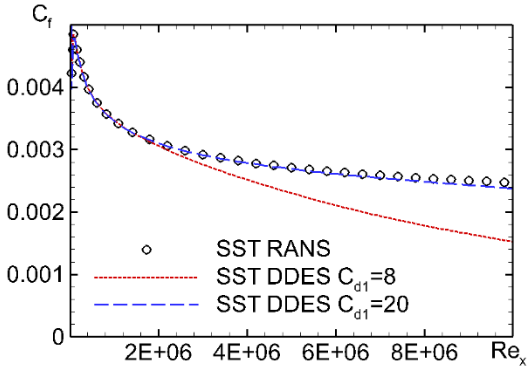

Fig. 7. The effect of the C_{d1} constant on the results of the flat plate boundary layer simulation.

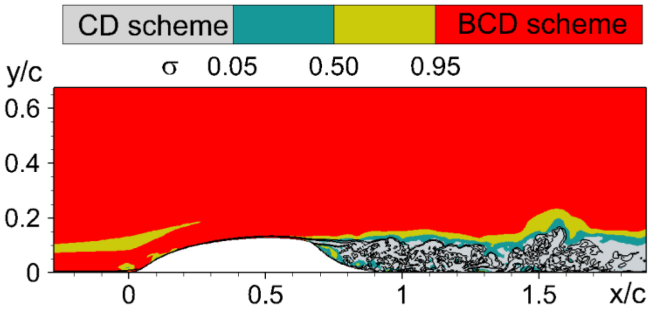

Fig. 8. The instantaneous field of the weighting function σ and the vorticity contours from the simulation of the flow around a bump on a surface. σ = 0 - central-difference scheme, σ = 1 - BCD scheme.

The last section of Chapter 3 (**Section 3.3**) is devoted to validation of the proposed HRLM enhancements by comparing the results obtained using them with the results of DNS and/or experimental data, as well as demonstrating their advantages over the basic models.

In particular, using the simplified version of the IDDES method based on the SST model for calculating the developed turbulent flow in a plane channel as an example, it is shown that the proposed simplification (**Section 3.3.1**) does not entail any noticeable decrease in the simulation accuracy.

Evaluation of the efficiency of the proposed versions of DDES, designed to accelerate the formation of developed turbulent structures in the separated mixing layers (the so-called “secondary transition to turbulence”), was carried out by calculating the flow in a channel with backward facing step, a supersonic baseflow, and flow around a hump on a flat surface (**sections 3.3.2 - 3.3.4**). A fixed separation takes place in the first two flows, whereas unfixed separation from the smooth surface is observed in the third one. All these flows are conventional tests of DES-like HRLMs and are widely used in the literature for validating models of this type. The obtained results convincingly indicate that the proposed models (the σ-DDES and

SST DDES in combination with a shear layer adapted subgrid scale Δ_{SLA} - the SST DDES Δ_{SLA} model) do provide significant acceleration of the formation of developed three-dimensional turbulence after the boundary layer separation. The simulation results confirming this conclusion are presented in Fig. 9, which shows the visualizations of the considered flows obtained with using the standard SST DDES method and its proposed modifications.

One can see that using of original version of SST DDES results in significant delay in the development of three-dimensional structures in the separated mixing layers for all the considered flows: in a sufficiently long initial section such structures are essentially absent (for example, for a backward facing step its length is about $2H$). In contrast, both proposed methods for accelerating the RANS-LES transition provide generation of resolved turbulence almost immediately after the separation point. In addition, resolution of noticeably smaller turbulent structures in the recirculation zone and in the region of relaxation of the turbulent boundary layer downstream from the reattachment point is also achieved using the improved methods.

The increase in calculation accuracy achieved due to suggested modifications compared to the original DDES method is clearly demonstrated Fig. 10. It should also be noted that a comparison of the simulation results obtained using the NTS and ANSYS FLUENT codes, also presented in this figure, indicates that the results of σ-DDES and DDES Δ_{SLA} are virtually independent of the code used. In contrast to this, the standard DDES results obtained using two codes significantly differ. The difference is because the length of the transition area formed within the DDES framework is very sensitive to the dissipative properties of the numerical scheme used, and the proposed DDES modifications practically exclude the occurrence of this area.

Finally, the final section of Chapter 3 (**Section 3.3.5**) presents the results of testing the proposed zonal approach using the volumetric turbulence source formulated in Section 3.1.3, using the compressible ($M_\infty = 0.5$) flat plate boundary layer.

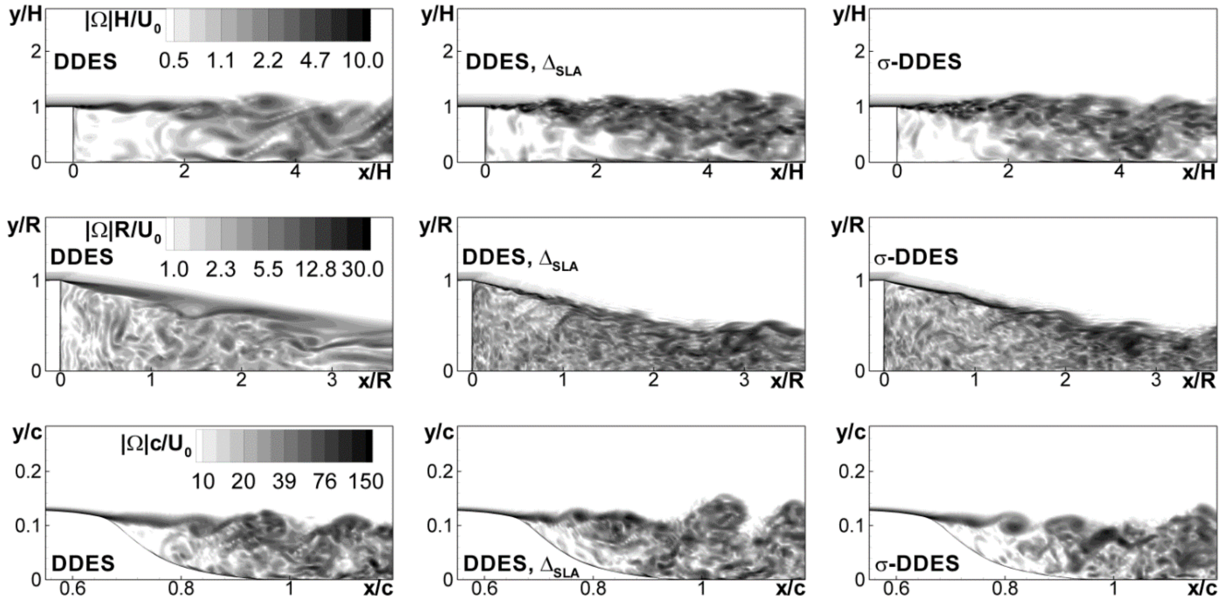

Fig. 9. Snapshots of vorticity magnitude in the XY plane. From top to bottom: flow in a channel with backward facing step, supersonic baseflow, and flow around a hump on a flat surface.

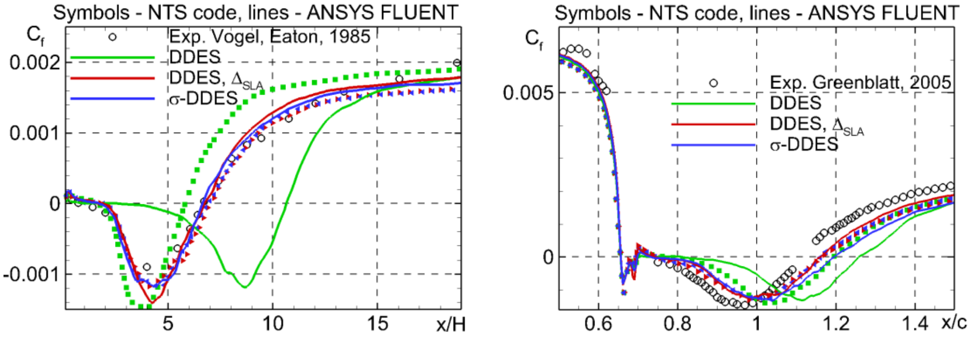

Fig. 10. Comparison of the skin friction coefficient distributions downstream the backward facing step (left) and downstream the hump (right) obtained with different models using the NTS code and ANSYS FLUENT with experimental data.

Chapter 4 is devoted to the application of hybrid RANS-LES approaches for calculating complex wall-bounded flows, some of which are considered for the first time. The obtained results demonstrate the capabilities of HRLM and their important advantages in comparison with the RANS approach.

Section 4.1 discusses the transverse flow around a tandem of cylinders. A number of complex physical phenomena are observed in this flow, which are inherent to flows around many real configurations containing two or more bodies (aircraft landing gear, wings of high-lift configuration, etc.). These include the separation of the turbulent boundary layer from the first cylinder, the formation of an unsteady turbulent wake behind it, and its interaction with the second cylinder, accompanied by the subsequent extensive separation of the flow from its surface. As shown in a number of works (and confirmed by the results obtained in the dissertation), the existing RANS models are not able to provide acceptable accuracy even for the average parameters of a given flow. At the same time, as can be seen from Fig. 11 and Fig. 12, the use of the IDDES method allows not only to describe the extremely complex structure of turbulence in this flow and to calculate its averaged parameters, but also to predict its statistical characteristics with high accuracy, in particular, the intensity of pressure fluctuations on the cylinder surfaces.

Sections 4.2 and 4.3 present examples of the application of the developed in the dissertation approaches to solve the problems of flow around multi-element aerodynamic airfoils used to increase the lift of a wing during take-off and landing of an airplane.

In particular, **Section 4.2** presents the results of simulations of the flow around a DLR-F15 three-element airfoil obtained using the modification of the SST IDDES method presented in **Section 3.1.1.** It is shown (see Fig. 13) that, as in the previous example, the hybrid approach provides not only adequate reproduction of the complex structure of turbulence in the flow, but also noticeably better than SST RANS agreement with experiment on its averaged characteristics (this advantage becomes apparent mainly near the slat and the initial section of the main wing).

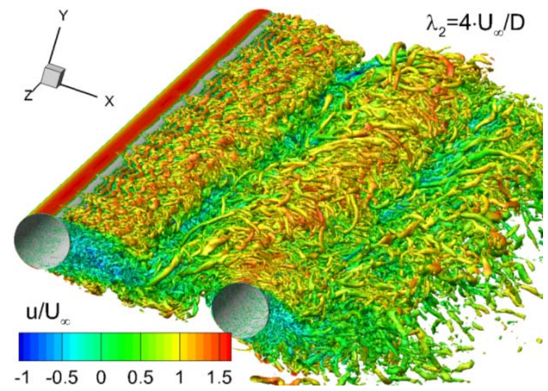

Fig. 11. Instantaneous swirl isosurface of value $\lambda_2 = 4$ from IDDES at $L_z/D = 16$.

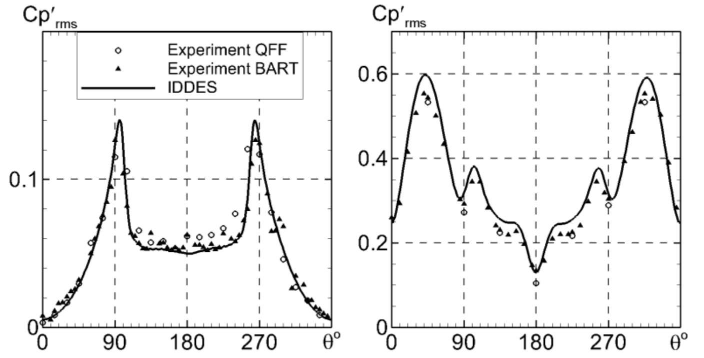

Fig. 12. Comparison of the distributions of the root-mean-square pressure disturbances over the surface of the front (left) and rear (right) cylinders obtained by IDDES with experimental data.

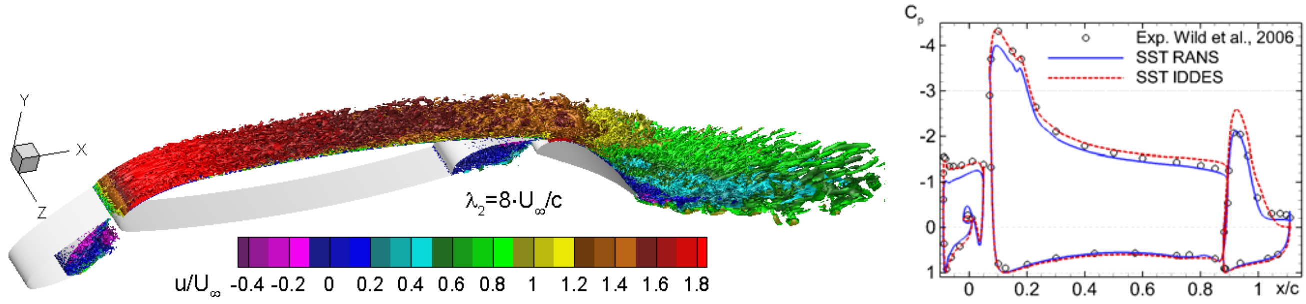

Fig. 13. Instantaneous swirl isosurface and comparison of the pressure coefficient distribution over the surface of the DLR-F15 high-lift airfoil obtained by the developed SST IDDES method with the results of SST RANS and experimental data.

Section 4.3 presents an example of the application of the zonal RANS-LES approach developed in the dissertation (see **section 3.1.3**) for solving aeroacoustics problems. It examines the flow around a wing-flap model configuration, which was studied as part of the VALIANT European Union project. This model configuration (see experimental setup diagram[5] in Fig. 14) contains the main wing of a long plate of finite thickness with a sharp trailing edge, and the flap by the NACA0012 airfoil. As can be seen from Fig. 14, the proposed approach provides the rapid formation of developed turbulent structures in the VS zone at the input boundary of the LES subdomain. At the same time, there is no generation of spurious noise (see visualization of sound waves in Fig. 15), which is a characteristic drawback of many other methods of creating artificial turbulent content at the LES input boundary. The calculated far-field noise spectrum obtained using the FWH method[6] (Fig. 16) is in good agreement with the measurement results in the range of 700 Hz$<f<$10 kHz (the difference with the experiment at $f<$ 700 Hz is associated with the presence of low-frequency background noise of wind tunnel).

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[5] Lemoine B., Roger M., Legriffon I. Aeroacoustics of a model non-lifting wing-flap system in a parallel flow // AIAA Paper 2011–2735, 2011.

[6] Ffowcs Williams J.E., Hawkings D.L. Sound Generated by Turbulence and Surfaces in Unsteady Motion // Philosophical Transactions of the Royal Society, Vol. A264, No. 1151, 1969. pp. 321-342.

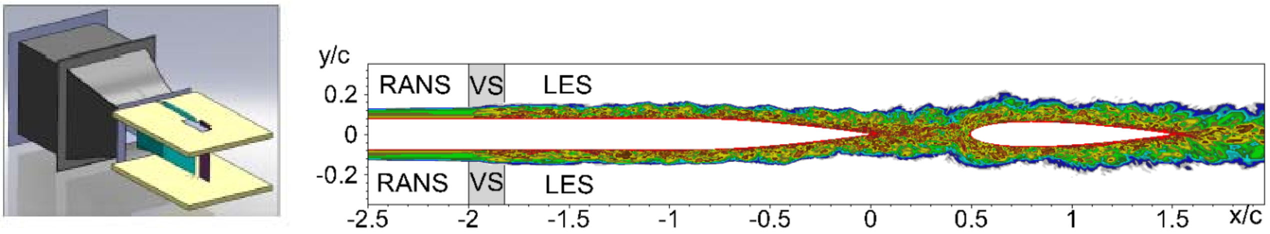

Fig. 14. Experimental setup (left) and visualization of the flow from simulation (snapshots of vorticity magnitude), also showing the position of the volume source zone (VS).

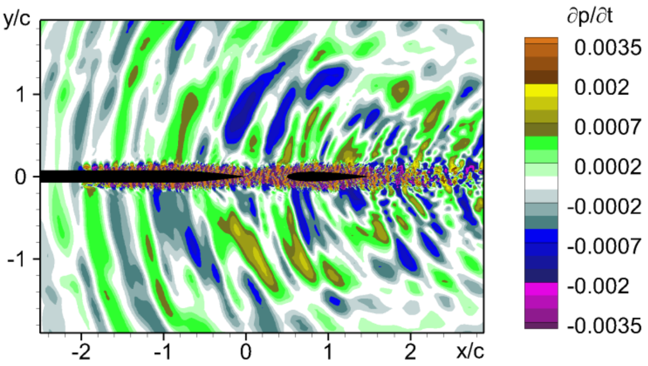

Fig. 15. Instantaneous field of the time derivative of pressure in the acoustic range.

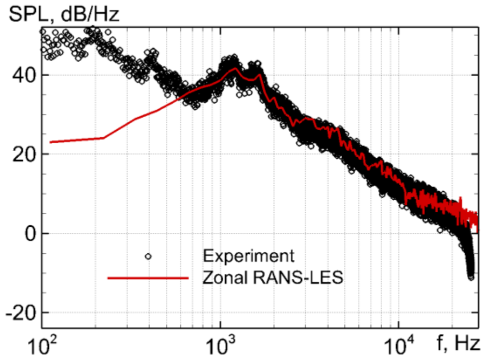

Fig. 16. Comparison of far-field noise spectra calculated using the FWH method with experimental data.

The simulation results presented in **Section 4.4** illustrate the wide possibilities offered by hybrid RANS-LES approaches, in general, and their versions developed in the thesis, in particular, when solving problems of aerospace engineering. A number of problems of this type is considered as examples, namely, problems associated with the calculation of unsteady aerodynamic and aero-acoustic loads on elements of manned spacecraft.

Section 4.4.1 presents the calculation of transonic flow around the reentry capsule using DDES, **section 4.4.2** describes the calculation of the flow around the head part of the spaceship using the two-stage zone IDDES method, and **section 4.4.3** describes the calculation of the flow around the manned spacecraft during emergency separation of the detachable head unit from the engine compartment using the zone two-stage DDES approach in combination with the shear-layer adapted subgrid scale Δ_{SLA}.

As an example, Fig. 17 shows the visualizations of the flow around the head part of a manned spacecraft during a transonic flight regime ($M_\infty = 0.85$) from a two-stage IDDES calculation. These visualizations convincingly indicate that this approach adequately describes both the extremely complex vortex and shock-wave structure of the considered flow. The dissertation also provides quantitative data on unsteady loads on a manned spacecraft surface, that appear due to interaction with turbulent structures forming in the boundary layer on the surface of the emergency rescue unit and in the wake of its nozzles. The results are presented at different nozzle locations, and set Mach numbers and angles of attack.

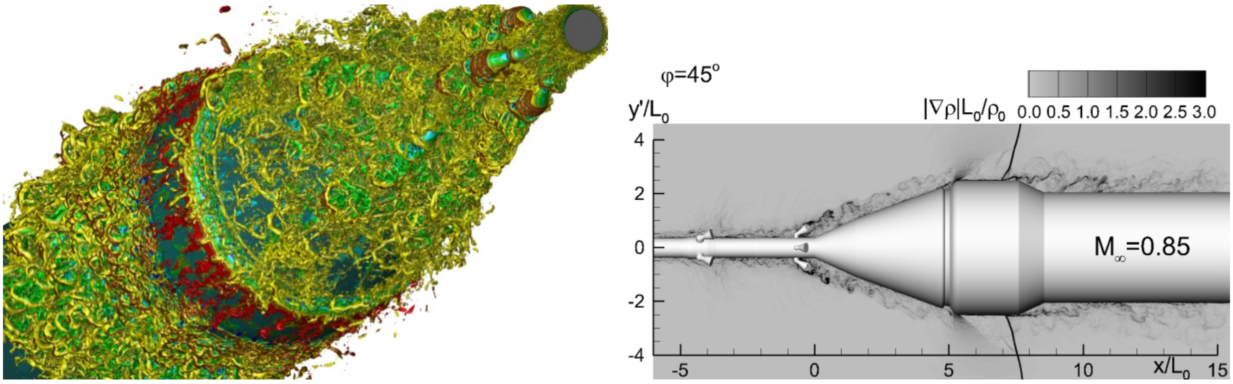

Fig. 17. Visualization of the flow around head part of the spaceship at M_∞ = 0.85: swirl isosurface and instantaneous density gradient fields ("numerical schlieren").

Another example that confirms the high efficiency of the proposed methods for accelerating the transition from RANS to LES in the framework of the SST-DDES method in calculating the emergency separation of the detachable head unit from the engine compartment is presented in Fig. 18. In particular, as can be seen from Fig. 18a, three-dimensional turbulent structures are quickly formed in the mixing layer detached from the edge of the returned vehicle (part of detachable head unit). It is shown in the dissertation that during transonic flight regimes at the initial stage of the separation process a standing sound wave forms in the gap between the detachable head unit and the engine compartment and large-amplitude pressure oscillations arise (see Fig. 18b). This, in turn, entails an increase in the acoustic load in the center of the frontal surface of the returned vehicle up to 165 dB and the appearance of pronounced tones in the spectra of pressure pulsations on the surface with frequencies from 80 Hz to 160 Hz (their presence is confirmed by experimental studies – see Fig. 18c).

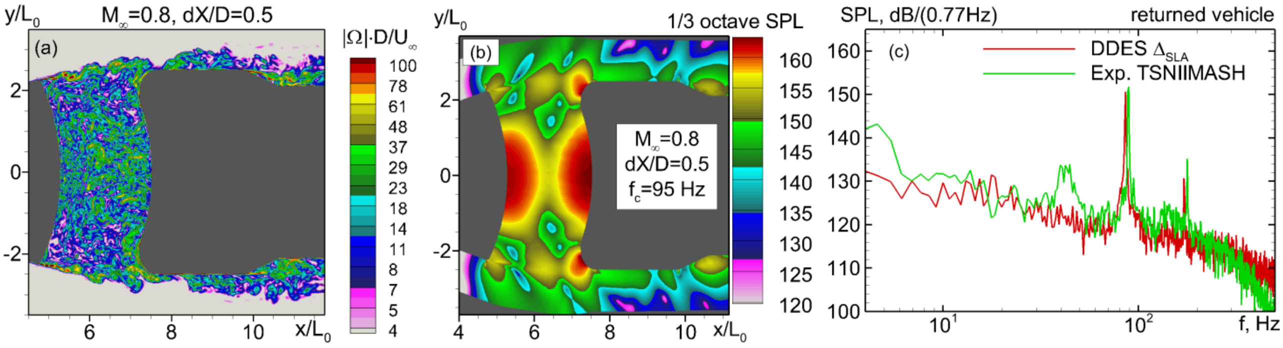

Fig. 18. Snapshots of vorticity magnitude (a), contours of intensity of pressure fluctuations in the gap between the detachable head unit and the engine compartment (b), and a comparison of computed and experimental power spectra on the surface command module screen (c).

The final **section 4.5** of **Chapter 4** presents the results of simulations of the transonic longitudinal flow around a cylinder with an axisymmetric bump, corresponding to the well-known Bachalo-Johnson[7] experiment. The simulations of this flow, the characteristic feature of

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[7] Bachalo, W.D., Johnson, D.A. Transonic, Turbulent Boundary-Layer Separation Generated on an Axisymmetric Flow Model // AIAA Journal, v. 24, No. 3, 1986. pp. 437-443.

which is the formation of a shock wave leading to separation of the boundary layer, were performed using both the zonal RANS-IDDES method and the zonal RANS-DNS-IDDES procedure, which required the use of the mesh of 8.3 billion nodes[8]. Some results of these calculations are presented in Fig. 19. This figure illustrates a qualitative change in the shape of wall turbulent structures downstream (from a region of zero pressure gradient to a region of acceleration of the flow before the bump and then in the region of interaction of the boundary layer with a shock wave, its separation and attachment to the streamlined surface). In addition, it gives a visual representation of the exceptionally small sizes of the vortex structures resolved in the simulation, and of the accuracy achieved in predicting the parameters of the averaged flow.

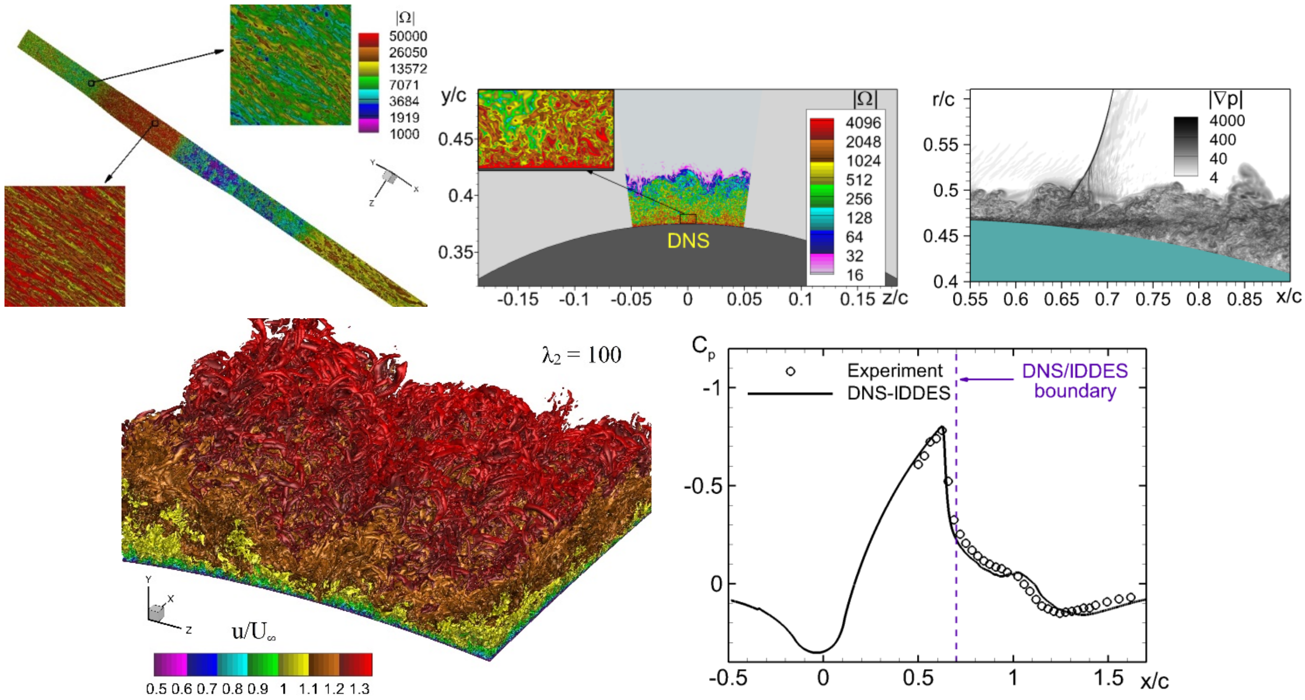

Fig. 19. Snapshots of vorticity magnitude on the surface and in the boundary layer in the vicinity of the middle section of the bump, the pressure gradient field in the vicinity of the shock wave (upper row), the swirl isosurface $\lambda_2 = 100$, and comparison of the pressure coefficient distribution from the RANS-DNS-IDDES calculation with experimental data (bottom row).

Chapter 5 of the dissertation presents the results of a series of the author's pioneering works on the application of the methods of the classical linear stability theory (LST) to the study of global stability of turbulent flows by linear stability analysis of the corresponding steady solutions of RANS equations. It should be noted that the validity of such an application of LST is not a priori obvious. Indeed, even the semi-empirical turbulence model used provides good agreement between the stationary RANS solution and the experiment, the error in prediction of the stability boundaries of the flow under consideration can be very significant. This is due to the fact that the LST is based on the assumption that the turbulence model used

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[8] At the time of this calculation, this grid was the largest in aerodynamic calculations performed in Russia and, as far as the author knows, this achievement has not been surpassed until now.

is not only suitable for describing a statistically stationary turbulent flow in the framework of steady RANS equations, but also for predicting the development of unsteady processes in frame of unsteady RANS equations. This circumstance must be taken into account when interpreting the results obtained.

Section 5.1 contains a detailed description of the developed approach intended for stability analysis of stationary solutions of the complete RANS equations for a compressible gas, closed using the SA model. Mathematically, the problem that needs to be solved within the framework of this approach is reduced to solving the generalized eigenvalue problem of a second-order linear differential operator $L(\bar{\mathbf{q}})$:

$$-i\omega\tilde{\mathbf{q}} + L(\bar{\mathbf{q}})\cdot\tilde{\mathbf{q}} = \mathbf{0}, \qquad (1)$$

obtained by linearization of the initial RANS equations, including the transport equation for the modified turbulent viscosity of the SA model. Here, the vector $\bar{\mathbf{q}}$ is a steady (“basic”) RANS solution, the stability of which is to be studied, $\tilde{\mathbf{q}}$ – is the complex vector of perturbation amplitudes, ω is their complex frequency, and i is the imaginary unit.

The result of solving this problem is a set of eigenvalues, the real parts of which are the frequencies of the corresponding perturbations, and the imaginary ones are the rates of their exponential growth or decay, as well as the set of eigenvectors corresponding to this set of eigenvalues. The presence of at least one eigenvalue with a positive imaginary part indicates the instability of the considered solution. In other words, if the largest imaginary part of the found eigenvalues is positive, then the solution is unstable, otherwise it is stable.

Section 5.2 describes the method developed for the solving system (1), in which this solution is numerically found on the same computational grid which was used for obtaining the steady (basic) RANS solution $\bar{\mathbf{q}}$. The discretization of the system of differential equations (1) and the corresponding linearized boundary conditions leads to the following generalized eigenvalue problem for the matrix *S*, which is a discrete analog of the linear differential operator $L(\bar{\mathbf{q}})$:

$$(-i\omega T + S)\cdot\tilde{\mathbf{a}} = 0, \qquad (2)$$

where $\tilde{\mathbf{a}}$ is the discrete analog of the vector of perturbation amplitudes, and T is the diagonal matrix in which the diagonal elements T_{ii} corresponding to the internal points of the region are equal to 1 and the others are equal 0 (the matrices S and T are of size $N_V \times N_V$, where $N_V = n_{var} \times N_p$, n_{var} is the number of main variables, N_p is the number of grid points).

This problem is solved using an Implicitly Restarted Arnoldi Method (IRAM) in combination with the shift-invert approach implemented in the Petsc/Slepc libraries and using the MUMPS library for LU matrix decomposition.

It should be noted that conducting a full three-dimensional stability analysis requires extremely large amounts of RAM. As an alternative, a simplified quasi-three-dimensional approach to the solving problem (1) was proposed in the dissertation, within the framework of which it is assumed that the basic solution is homogeneous in one of the spatial directions (*z*, for example), and perturbations in this direction are considered harmonic, i.e., the perturbation vector is represented as $\tilde{\mathbf{q}}_{3\mathrm{D}}(x,y,z)=\tilde{\mathbf{q}}_{\mathrm{q3D}}(x,y)\cdot\exp(i\beta z)$.

Section 5.3 is devoted to verification and testing of the developed method and corresponding software implementation.

So, the results of its application to solving problems of the stability of laminar flows are presented in **Section 5.3.1** (in this case, the transport equation of eddy viscosity is excluded from consideration, and the eddy viscosity and thermal conductivity in the momentum and energy transfer equations are assumed to be zero). The computational results were compared both with the solutions of the unsteady Navier-Stokes equations obtained in this work, and with data known from the literature, which allows us to verify a significant part of the developed algorithms. In particular, the following tasks were considered: the development of Tollmien-Schlichting instability in the channel, the stability of the laminar flow around a rectangular cavity in a flat wall, the stability of the Ekman layer and the stationary flow around cylinders of constant and variable diameter. In all considered cases, the results obtained using the proposed method are in good agreement with the results of other methods.

Section 5.3.2 presents the results of verification of the developed approach to stability analysis of steady solutions of RANS equations closed using the SA turbulence model. Verification was carried out by comparing with the unsteady RANS solutions for the following turbulent flows: Couette flow, the Ekman layer, flow around a straight wing of infinite scope. Comparison with experimental data known from the literature and the results of LES and DNS confirms the presence of instability predicted using the proposed approach. In particular, the direction of the vortex structures in the Ekman layer, predicted by the stability analysis, is consistent with the implicit LES results.

Finally, the last (main) **section 5.3.3** of the fifth chapter is devoted to the application of the developed methods for determining the parameters of the transonic buffet onset on the wings.

The results of a two-dimensional stability analysis for three different airfoils (Fig. 20) indicate a high accuracy in predicting the buffet onset, which is provided by the proposed approach. Thus, the critical angle of attack for the NACA 0012 airfoil is in good agreement with experimental data at $M_\infty \leq 0.79$. In this case, not only the instability with an increase in the angle of attack is predicted, but also the stabilization of the flow with the Mach number increase in (a noticeable difference with the experiment at the boundary Mach number $M_\infty = 0.8$ is most likely caused by the error introduced by the semi-empirical turbulence model). Similar results were obtained for the OAT15A and RA16SC1 airfoils.

The study of the infinite swept wing was carried out using both a full three-dimensional stability analysis, and a simplified quasi-three-dimensional approach.

An analysis of the results revealed two types of instabilities (Fig. 21 - Fig. 22).

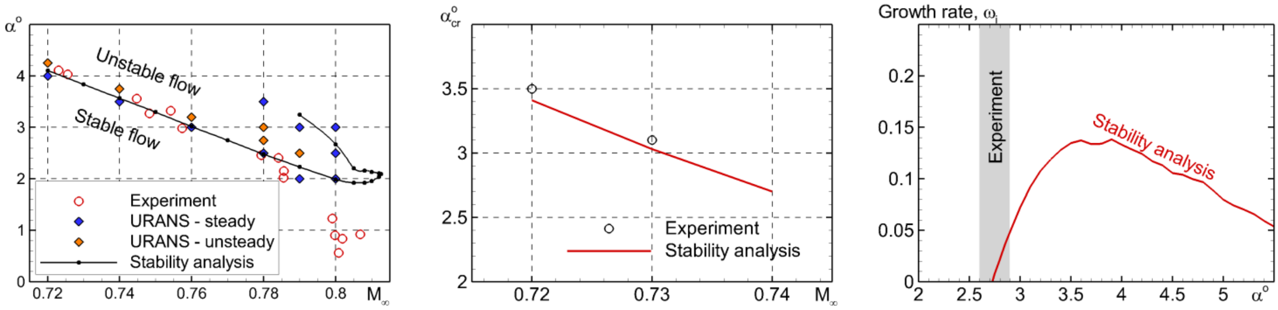

Fig. 20. Comparison of stability analysis results with experimental data for NACA0012 (left), OAT15A (center) and RA16SC1 (right) airfoils.

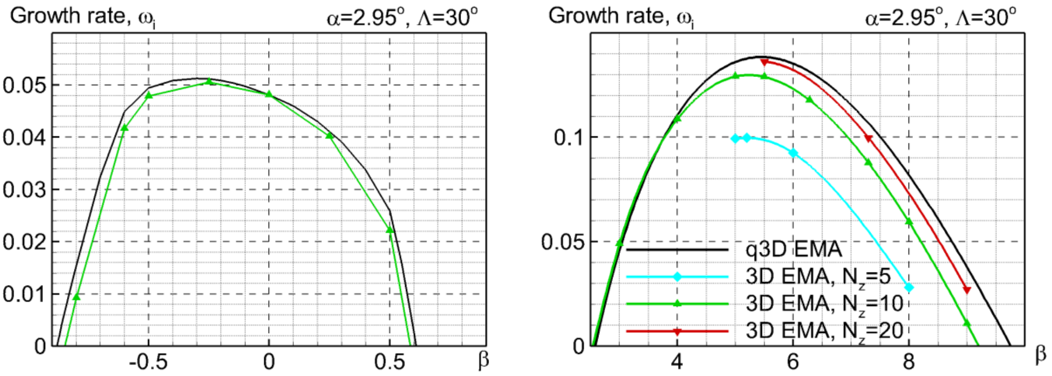

Fig. 21. The dependence of the growth rate on the wave number for the first (left) and second (right) types of instability for the OAT15A airfoil at the angle of attack α = 2.95° and sweep angle Λ = 30°. The results of quasi-three-dimensional analysis and full three-dimensional analysis are presented for different number of cells along the transverse coordinate N_z.

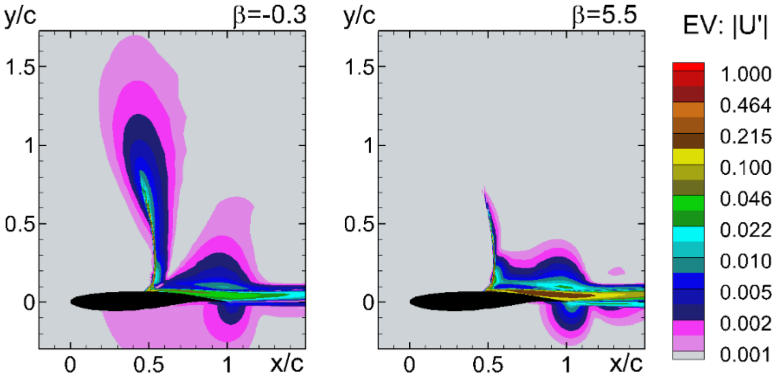

Fig. 22. Examples of eigenvectors obtained in the framework of the quasi-three-dimensional approach at angle of attack α = 3.03° and sweep angle Λ = 30° for β values corresponding to the maximum instabilities of the first and second types of instability.

Perturbations arising during the development of instability of the first type are characterized by relatively large wavelengths in *z*-direction ($\lambda_z/c > 6$), which correspond to the wave numbers $|\beta| < 1$ (this type of instability includes, in particular, perturbations uniform in z corresponding to $\beta = 0$). The wavelengths of disturbances of the second type range from 0.5*c* to 3*c*, which corresponds to wave numbers β from 2 to 10 (this type of instability is observed in an experimental study of buffet on the swept wing of passenger aircraft). The amplitudes of the eigenvectors of perturbations corresponding to the longitudinal velocity component for the most unstable modes of the first and second types are shown in Fig. 22. It can be seen that for instability of the first type, the maximum amplitude of the velocity perturbations is reached in the vicinity of the shock wave (in the separation zone and after the profile, the amplitude of these perturbations is approximately 20 times smaller). In contrast, for perturbations of the second type, the difference in amplitudes at the shock and in the wake is less significant (their ratio is about 5).

Finally, it should be emphasized that the computation results obtained using the quasi-three-dimensional and full three-dimensional stability analysis are in good agreement with each other (see Fig. 21), however, to obtain a sufficiently precise solution in the framework of the three-dimensional approach, it is necessary to use a fine computational grid along the transverse coordinate , which is hardly possible when solving real problems due to the limited resources of even the most powerful of modern computer systems. This confirms the efficiency and great practical significance of the quasi-three-dimensional approach proposed in the dissertation.

The main results of the work are formulated in the **Conclusion**.

1. Possible ways to improve existing methods for numerical modeling of wall-bounded turbulent flows have been identified, based on their analytical review.
2. A number of the original modifications of the two most successful semi-empirical turbulence models for wall-bounded turbulent flows have been developed, namely, for the Spalart-Allmaras eddy-viscosity transport model (SA model) and for the Menter two-equation SST model (SST model). In particular, proposed:
   - two nonlinear models designed to compute flows in which the anisotropy of Reynolds stresses plays a significant role;
   - two modifications of the SST linear model, the first of which increase the accuracy of the prediction of flow with significant streamline curvature and rotation and the second one is for computations the flows around airfoils at stall conditions;
   - two modifications of the SA model, the first of which provides an increase in the accuracy of computation of axisymmetric flows, and the second - the accuracy of the computation of the attached boundary layers at low Reynolds numbers.
3. The proposed models were verified by comparing the obtained results with the use of two different CFD codes (ANSYS FLUENT and NTS code), and their extensive testing by comparing with experimental data and direct numerical simulation results. It is shown that the developed models are superior in accuracy to both the basic SA and SST models, as well as existing analogues.
4. Substantial enhancements to hybrid RANS-LES approaches have been proposed, namely:
   - new versions of global DDES and IDDES methods based on k-ω SST model, surpassing original versions in accuracy;

- new DES-like hybrid RANS-LES model SST σ-DDES, providing significant acceleration of the formation of three-dimensional resolved turbulent structures in the separated mixing layers;
- effective technology for implementing a one-stage zonal RANS-LES approach using volume sources in the momentum and turbulent kinetic energy transfer equations to generate turbulent content at RANS-LES interface, applicable on arbitrary, structured and unstructured grids.

5. A new hybrid scheme for the inviscid fluxes in the transport equations for hybrid RANS-LES approaches has been developed, which ensures the stability of the algorithm and high accuracy of the resolution of turbulent structures in both attached and separated wall-bounded flows.
6. Comprehensive testing of the developed hybrid models and methods was carried out based on comparison of the obtained simulation results with known experimental data and the results of direct numerical simulation.
7. New detailed quantitative data were obtained using hybrid RANS-LES approaches on the aerodynamic and aero-acoustic characteristics of a number of complex wall-bounded flows, some of which were considered for the first time:
   - tandem cylinder flow;
   - flow around DLR-F15 high-lift airfoil;
   - flow around the wing-flap model configuration;
   - trans- and supersonic flow around the reentry vehicle and the detachable head unit of the manned transport ship in take-off mode and during emergency separation from the launch vehicle.
8. A new zonal RANS-DNS-IDDES approach was developed and used for simulation of shock-boundary layer interaction with subsequent separation and attachment in the transonic flow over a bump on a cylindrical surface using a grid with an unprecedented 8.3 billion nodes.
9. A new approach to the analysis of the global stability of turbulent flows, based on a linear stability analysis of steady solutions of RANS equations, including the transport equations of turbulence characteristics, is proposed. The approach was implemented as a set of algorithms and computational programs which is suitable to define existence and development of global temporal and spatial instability in two- and three-dimensional turbulent flows.
10. A thorough verification of the suggested approach and developed software implementation was carried out on a wide range of problems on the stability of laminar and turbulent flows:
    - the development of Tollmin-Schlichting instability in the channel;
    - the stability of the laminar flow around a rectangular cavity in a flat wall;
    - the stability of the laminar and turbulent Ekman layer;
    - the stability of the laminar transverse flow around the cylinder of constant and variable diameter;

- the appearance of longitudinal vortices in turbulent Couette flow;
- the appearance of vortex cells in the turbulent flow around infinite wing at stall conditions.

11. New results regarding the conditions for the transonic buffet onset on the straight and swept wings were obtained using the developed approach and software.

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