

Current Visualization Trends in CFD Problems

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Abstract

The paper presents authors view at the current trends of visualization in CFD (computational fluid dynamics) problems. The main factors of influence defining these trends are considered. Some examples of methods synthesis for better insight of numerical experiments data are enclosed. Also the prospects of such synthesis applying to construction of generalized experiment are discussed.

Mathematics Subject Classification: 76N25, 76M27, 65Y05

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1 Introduction

The paper presents a brief survey of current trends in visualization of numerical data in CFD (computational fluid dynamics). We consider the numerical data as numerical results produced by methods of mathematical modeling of CFD problems. The review is primarily based on current Russian studies in scientific visualization.

Visual presentation of numerical results in scientific researches is a very important branch of knowledge. Without using modern concepts, methods, and software for scientific visualization, it is impossible to completely and reliably analyze the results of numerical simulation of complex physical and engineering processes carried out on modern computers. Scientific visualization methods were

elaborated to present the numerical solutions for direct problems in CFD modeling – mostly for 2D and 3D time-dependent processes. The development of visualization tools and methods was always in pursuit of the capabilities of numerical methods for CFD modeling. The evolution and development of concepts, methods, and approaches of visual representation of numerical results obtained in computational physics are thoroughly considered in [6].

For direct problems in CFD modeling one has traditional scheme for implementation of numerical experiments. The scheme looks quite standard. Having some mathematical model for description of time-dependent CFD process and reliable numerical method for simulation we are able to simulate the direct problem for this process. Then visualization methods provide a possibility of numerical data analysis. For many particular cases in practice visualization is the only way to understand the sense of physical process under consideration. At the same time visualization allows us to verify the results. Basing on this verification one can correct mathematical model and numerical method applied for solving (if it is needed) with purpose to optimize them. The scheme of numerical experiment for direct CFD problem is presented in general form in Fig. 1.

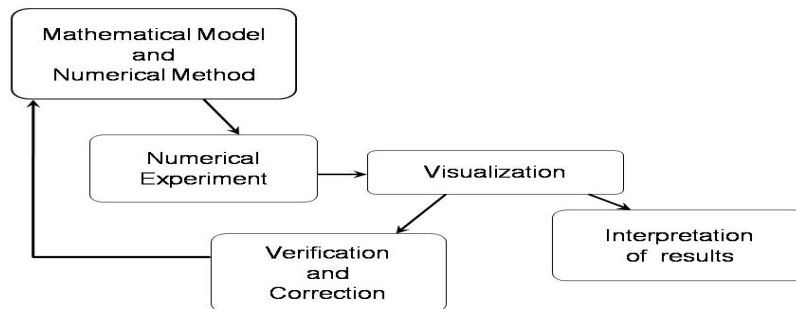


Fig.1. General scheme of numerical experiment for direct CFD problem.

Such classic scheme of numerical experiment was elaborated in accordance with the level of complexity of problems to be solved and to the level of computer hardware and mathematical methods. Nowadays, the development of computer hardware and the appearance of supercomputers and parallel computing provide us by new capabilities and new challenges. It leads to the forming of new fields of research and new computational problems.

2 Main factors of influence

We can mark some main factors defining current trends for mathematical modeling of CFD problems. These trends form new visualization problems requiring the development of new concepts and approaches.

The first factor is intensive development of high-performance computing and parallel algorithms. This factor is basic. It is especially important for CFD problems because application of parallel computations allows transferring CFD mathematical modeling to new level. Being applied to direct CFD problems parallel computing provides increasing of calculations velocity. Also parallel computing allows usage of thorough grids in numerical experiments. Naturally, it makes the numerical experiments for standard direct problems very effective. But real new level is an opportunity to solve multidisciplinary problems, inverse problems and parametric researches. As it is known these three types of problems are high-priority tasks for modern parallel computations. Multidisciplinary problems provide combination of models for different physical processes in one numerical experiment. Inverse problems are problems where causes for a desired or an observed effect are to be determined. The causes are unknown so one should determine them basing on observation of their effects. This is in contrast to the corresponding direct problem, whose solution involves finding effects based on a complete description of their causes. The inverse problems are very important for practical engineering, where the typical problem is the choice of desired variant from the set of admissible ones. This can be the choice of a geometric shape, the choice of flow control, etc. Parametric researches allow to get numerical solution not for particular CFD problem only, but for the whole class of problems. For such cases the class of problems is defined in multidimensional space created by characteristic (or determining) parameters of the problem under consideration. These characteristic parameters are varying in definite ranges. Parametric researches are very difficult and require a lot of computer resources. But parametric optimizing analysis is the most difficult numerical research. It is a kind of standard parametric research where the inverse problem is considered for each point of grid in multidimensional space of characteristic parameters instead of direct problem. This type of numerical research is intended for finding the domains in the space of determining parameters where a phenomenon of interest occurs for a certain class of problems.

Such types of numerical research have one specific feature from the point of view of visualization. Their numerical results are presented in general discrete form as multidimensional arrays for grid points set in the space of characteristic parameters. The dimensionality of such array corresponds to the quantity of determining parameters. The arrays need processing and visual presentation for analyzing and comprehension. Visualization methods are applied to such array with purpose to bring out hidden dependencies.

For these purposes one should combine visualization approaches with Data Analysis methods for decreasing of dimensionality [5]. It is necessary due to the evident lack of visualization concepts and tools for spaces having more than 3 dimensions. Also one should take into account the fact that many of mentioned above numerical researches use optimization statement of problem under question. So optimization process in computations should be visualized as well.

The next important influencing factor is digital revolution which has happened in experimental flow dynamics. The revolution in experiments was caused by total

transfer to digital technologies for flowfield images registration and visualization of experimental results. Some aspects of this process are described thoroughly in [9], where main flow visualization methods are revised: optical methods based on the refraction, dispersion, absorption, re-emission, polarization, methods of surface visualization; tracing. It is noted in [9] the fact that digital revolution leads to possibility of direct comparison of experimental and computational results in fluid dynamics. Such direct comparison increases effectiveness of research and allows improving as experiment conditions as numerical methods. Examples of comparison of numerical and experimental flow visualization, produced by different imaging techniques are shown in [9]: shadow, PSP (Pressure Sensitive Paints) images, BOS (Background Oriented Schlieren) method, PIV (Particle Image Velocimetry) images, visualization by discharge, etc. Visual convergence of experimental and computational results provides an opportunity to apply known and reliable methods of image processing to experimental data with purpose to define hidden flow structures and to trace them. Application of image processing methods can be also useful for elimination of experimental artifacts in results.

The third factor of influence is rapidly growing confluence of mathematical and numerical methods developed in different fields of knowledge. Such synthesis allows getting of new results for many complicated problems. For instance, image processing methods can be successfully applied for finding of hidden structures (discontinuities) in CFD results [2, 4]. For problems of flow identification and flow control with usage of adjoint equations the visualization of adjoint parameters and control functional allows implementing the control of process under consideration [3]. For problems of searching of hidden dependencies and for problems of data classification one can apply Data Analysis methods such as cluster analysis methods, factor analysis methods, PCA (Principal Component Analysis) methods and its modifications for nonlinear cases. Such mutual enrichment of different methods and approaches is very useful. It has great potential perspectives.

3 Examples of current research trends

The problems of parametric optimizing analysis and visualization of results presented in a form of multidimensional data array are considered in [5]. The paper presents an approximate approach to analysis of space–time structures appearance in the flow. This approach is intended for fast and rough estimation of unsteady flow structures dependence on characteristic parameters in a certain class of problems. The approach is based on optimization problem solution combined with methods of data visual presentation. Optimization problem solution is implemented by parallel computation in a multitask form. The visual presentation methods are applied for analysis of multidimensional array containing discrete result data. Visualization is used with purpose to bring out hidden dependencies. For some cases, the approach allows to obtain for control

parameter of considered problem the sought-for approximate dependence on characteristic parameters.

Fig. 2 illustrates approach application to the problem of unsteady interaction of the supersonic viscous flow with jet obstacle. This obstacle appears due to co-current underexpanded jet exhausting from the nozzle. The nozzle is placed to external supersonic viscous flow. Expanding jet propagates on the external surface of the nozzle creating obstacle in external flowfield. Typical flow structure is shown in Fig. 2(a) by streamlines. Time-dependent control action (the velocity of pressure ratio growth in underexpanded jet) allows to change time-space structure of flowfield (Fig. 2(b)). The main target of research is estimating and defining the control parameter dependence on four characteristic parameters of the problem – Mach, Reynolds, Prandtl and Strouhal numbers. These parameters are varied in definite ranges creating four-dimensional space. Fig.2(c) presents the sought-for dependence after data analyzing intended for decreasing of dimensionality. As a result the dependence can be roughly approximated by plane.

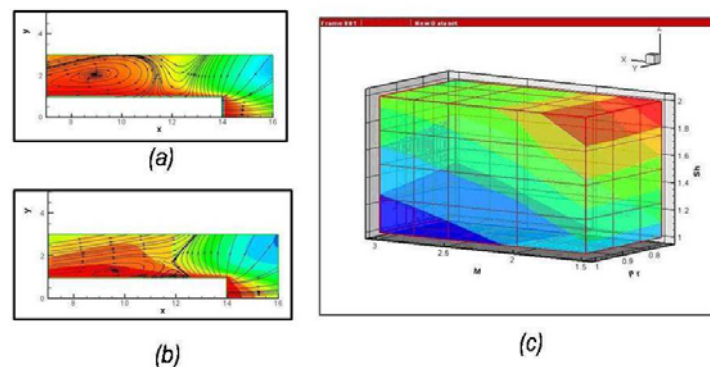


Fig.2. Parametric optimizing analysis applied to jets interaction [5].

Another direction of research is very close to previous one. To analyze some physical effect in time-dependent process one should be able to detect the effect. The problems of time-dependent flow structures finding, detecting, visualizing and tracing are very important. We consider discontinuities and vortexes in the flowfield as specific structures which should be detected.

Searching vorticity zones in the flowfield one should use mathematical methods developed in mathematical physics for such problems. Paper [8] contains thorough description of these methods. The methods allow effectively tracking the critical points of the flow and observing time-dependent processes of vortex formation and disintegration. The example of vortexes detection and visualization is presented in [7] for time-dependent 3D flow. Paper [7] considers application of different visualization methods to the problem of wingtip vortex interacting with a bow shock. The shock is generated by cylinder obstacle mounted downstream of the wing edge. The paper is focused on comparison of visualization results for two most widely used methods of vortex detection: density distribution method and Lambda-2 method.

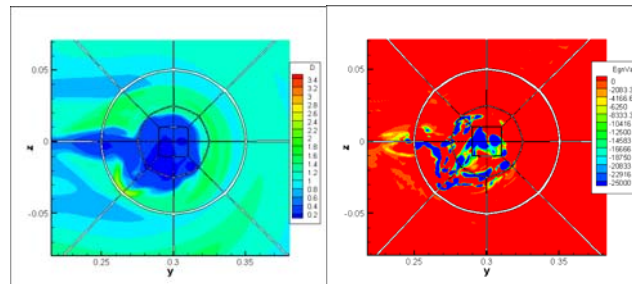


Fig.3. Visualization for different methods of vortex detection (left - density distribution, right - Lambda-2 method) [7].

Typical results are presented in Fig.3. The results are shown in cross-section passing through the thick of the interaction domain (of a wingtip vortex with a head shock wave). By means of density distribution one can see only a boundary of vortex zone and not enough details. Through lambda-2 method one can't see exactly the boundary, but it is possible to see details inside.

Analyzing the flowfield we have another important problem. The problem is detecting of discontinuities in the flowfield under consideration. This direction of research presents an example of synthesis of methods developed in different fields of knowledge. A method for highlighting structures in solutions based on applying image processing algorithms to the flowfield data was proposed for the first time in [4]. The aim of that approach is to automate processing of the numerical result of gasdynamic flow simulation so as to obtain the structure of its strong discontinuities. Under this approach, gasdynamic functions determine the intensity of the image and the values of these functions at every point are considered as pixels. A detector of sharp difference in the values is used, and the detected discontinuities are classified using discrete analogs of gasdynamic equations satisfied on the discontinuity. An example of the application of this approach is shown in Fig. 4. The picture presents the curves of equal density for original computational results and points of discontinuity obtained by image processing methods.

This approach is independent of the specific problem, and it does not require any a priori information about the flow. It can be applied to the results obtained using any shock capturing method; furthermore, it speeds up the processing of the results of numerical simulation and improves the quality of the result interpretation. The sense of this approach is detection of discontinuities which cannot be detected by any other ways including direct visualization of the flowfield. To display the sought-for structures in the standard flowfield image one should use image processing methods.

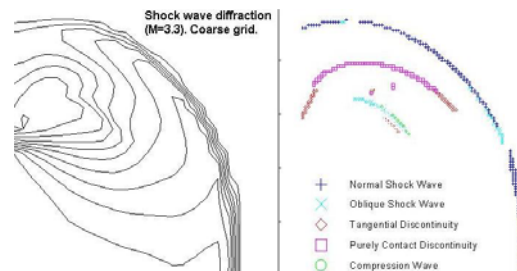


Fig.4. Curves of equal density and points of discontinuity obtained by image processing [4].

This line of development received a new impulse based on the use of powerful mathematical apparatus of wavelet analysis. Paper [2] is devoted to distinguishing and classification of singularities of gasdynamic fields, such as shock waves and weak and contact discontinuities. The algorithm proposed in [2] is based on expanding the original gasdynamic fields in terms of wavelet basis with the subsequent analysis of the coefficients. Paper [2] generalizes initial approach [4] to 3D case and to the case of viscous flow. Also method described in [2] allows to adopt computational grid to discovered discontinuities.

All discovered structures in the flowfield (vortexes and discontinuities) are obtained by computations. These results should be verified by comparing with experimental results for the problem under consideration. Current state-of-the-art in experimental visualization of fluid dynamics problems is presented in [9]. This paper presents modern experimental methods and approaches allowing direct comparison of numerical and experimental results. The comparison has become possible because of transfer to digital technologies of data registration and visualization in experiments. This transfer was called as *digital revolution*. Author notes the fact that mutual implementation of experimental and computational modeling allows to solve some inverse problems. Such inverse problem can be finding of unknown parameter by comparing the numerical and experimental images with known controlled parameters. Eliminating differences in experimental and numerical visualization of gas-dynamic flow one can get the way to correct solution. At the same time the comparison of experimental and numerical visualization enables a possibility to verify both models: computational and experimental.

An example of mutual implementation of computations and experiments is presented in [9]. This paper considers the analysis of the flow with energy deposition. The inverse problem of finding the spatial energy distribution for localized energy deposition is solved by comparing the numerical and experimental images with known controlled parameters. The paper presents the results of the spatial distribution of the combined energy of the pulsed nanosecond discharge investigation by the method of analyzing the dynamics of two-dimensional shock-wave configurations. The configuration and evolution of

the discontinuities arising from the interaction of the discharge with a plane shock wave in the channel are described. An example of experimental (Fig.5a) and numerical results (Fig.5b) is presented below.

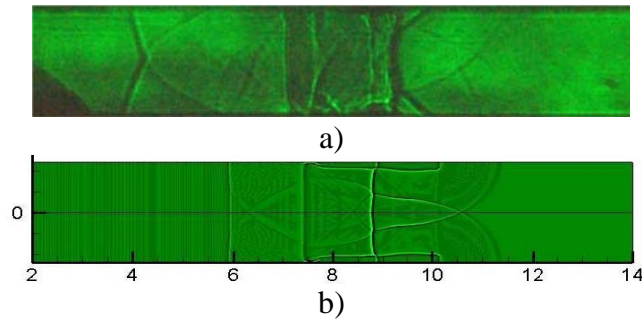


Fig.5. Discontinuities in the flow with energy deposition: a) experimental result, b) computed result [9].

This approach allows to determine the value of energy deposited in a pulsed electric discharge and its localization in the flow area. It is shown that direct comparison of digital numerical and experimental flow fields can be effective tool for the analysis of hydrodynamic processes.

Another direction of research is presented by problems based on combined application of adjoint equations and visualization methods. Adjoint equations make it possible to solve many CFD inverse problems including problems of flow control and identification. For these problems adjoint parameters are used to calculate the gradient of the objective functional. Visualizing of adjoint parameters one can find zones of the most effective control and choose measurement zones. Also the field of adjoint parameters makes it possible to calculate and visualize the contribution of the errors in the initial data, in the physical model, and discretization errors to the error in the objective functional. This can be used to reduce the error and to obtain a solution with the required guaranteed accuracy. The particular example of such research is presented in [3], where the problem of oblique shock waves interaction is considered. The paper [3] considers inverse problem of finding energy deposition providing transfer from regular reflection to Mach reflection (Fig.6). Visualization of adjoint energy is presented in Fig.7 for both types of reflection. Visual presentation of adjoint parameters allows to define the distribution of the sought-for energy deposition. Also using adjoint parameters one can estimate different types of errors in solution. Approach [3] provides determination of irremovable error. The information about these zones is very useful for construction of adoptive grids in numerical experiment.

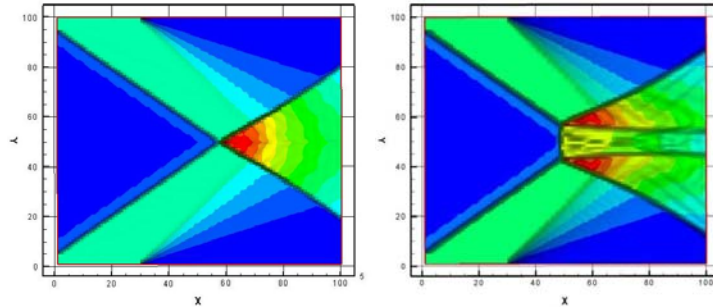


Fig.6. Density isolines for shock waves interaction: left - regular reflection, b) right - Mach reflection [10].

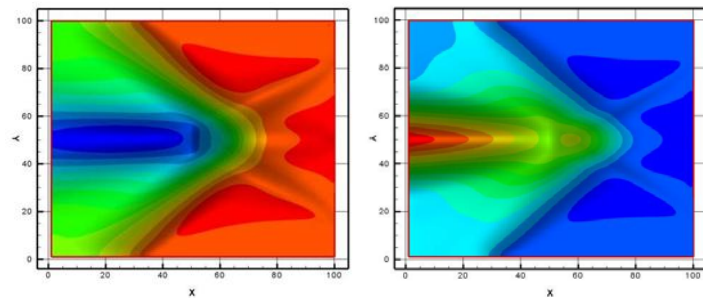


Fig.7. Isolines for adjoint energy: left - regular reflection, b) right - Mach reflection [10].

Solving the problems of parametric researches and parametric optimizing analysis we have to process obtained results. As a rule the results are presented in discrete form as multidimensional arrays, where number of dimensions is more than three. At the same time all methods and tools in CFD visualization were elaborated for 3D time-dependent flows, so we are able to work confidently with $(3 + 1)$ dimensions. In this situation it is quite natural to use integration of traditional scientific visualization approaches with *Data Analysis* methods. Such integration grows rapidly. This trend of research can be marked as very prospective. Applying *Data Analysis* methods to the processing of multidimensional data we can define and evaluate main influencing factors. We are able to find hidden dependencies between these factors. Also with the help of these methods we can consider the problems of clusterization and classification for objects inside multidimensional domain under question. Using PCA one can present obtained data in new space created by principal components. The fact of importance is ability to decrease dimensionality of multidimensional array under consideration. An example of such decreasing is considered in [5]. The decreasing of dimensionality allows to apply CFD visualization methods and tools for some cases. Nevertheless simple mechanical application of *Data Analysis* approaches to CFD multidimensional data is not always effective due to specificity of problems and data. The perspective platform for such integration can be built on a base of functional approach FRep (Functional Representation) described in [1]. The

advantage of this approach is the fact that the approach initially presents the objects for visualization as functions of multiple variables. This presentation allows to create the system of operators defining objects transformations and relations between objects. The approach can be considered as suitable one for CFD multidimensional data processing and analyzing. Modeling on the basis of FRep can be performed using a high-level language HyperFun and supporting its software tools. HyperFun is an international free and open source software project on FRep modeling, visualization and animation.

4 Generalized experiment

In previous section we have considered some examples of CFD numerical experiments marking definite modern trends in researches. Nowadays these trends are quite separate. But analyzing these trends one can assume future integration of mentioned above approaches in a whole set. The integration would allow an implementation of *generalized experiment* for fluid dynamics problems. The possible scheme for implementation of such generalized experiment is presented in Fig.8.

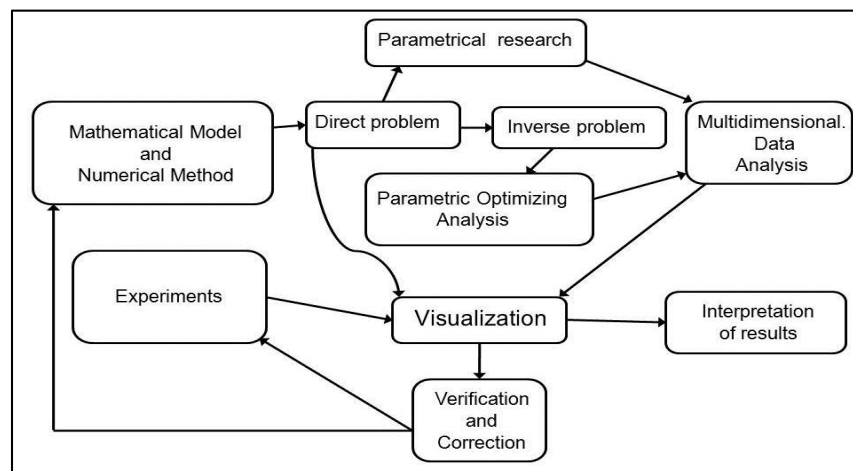


Fig.8. Scheme of generalized experiment.

This experiment is to be based on reliable mathematical model, numerical method and capabilities of experimental research. The methods for searching and tracing of time-dependent structures in the flow under consideration should be integrated in the set of methods. Such generalized experiment should be able to solve inverse problems and optimization problems. During the process of numerical computation the results are to be directly compared with experimental ones for all possible cases. It would provide the process of constant verification. Being implemented by means of parallel methods the properties mentioned above would provide a possibility of parametric research and parametric optimizing

analysis. These approaches would give us the results in a form of multidimensional arrays. To analyze the results one should use Data Analysis methods, which should be integrated in the set of numerical methods for generalized experiment. Finally the future generalized experiment would provide solution for classes of CFD problems. It can be very effective for practical applications. Constant verification is to be used for improving of numerical methods and conditions of experiment. Also the verification would allow to increase reliability of results. The results of generalized experiment would provide solving of practical problems for flow control in CFD.

Constructing technology of future generalized experiment one should place visualization at the key point. Visualization would be used for data analyzing, processing, interpreting and verifying at all stages of experiment. Visualization would be used as a main tool for connecting of all approaches of generalized experiment in a whole set. For such experiment the general problem of visualization is divided into subproblems such as:

- visualization of direct problem solution;
- search and visualization of time-dependent structures in the flows;
- optimization process visualization;
- visualization of hidden dependencies in multidimensional volume of data;
- image processing with purpose to compare directly experimental and computational results.

5 Conclusions

In this brief survey we present our point of view at some current trends dealing with development of visualization in CFD modeling. All considered trends appeared due to the set of influencing factors which are also marked in this paper. We consider the examples of computational approaches illustrating the trends. The examples include the search of space-time structures in flowfield, applications of adjoint equations for flow control, processing of multidimensional solutions for parametric researches. The perspective of generalized experiment construction by integration of considered approaches is discussed.

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