Supercomputer modeling of flow past hypersonic flight vehicles

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Abstract. A software platform for MPI-based parallel solution of the Navier-Stokes (Euler) equations for viscous heat-conductive compressible perfect gas on 3−D unstructured meshes is developed. The discretization and solution of the Navier-Stokes equations are constructed on generalized S.K. Godunov's method and the second order approximation in space and time. Developed software platform allows to carry out effectively flow past hypersonic flight vehicles simulations for the Mach numbers 6 and higher, and numerical meshes with up to 1 billion numerical cells and with up to 128 processors.

1. Introduction

For the X−43 model of hypersonic flight vehicle, that made three demonstration unmanned flights in the NASA Hyper−X program, the supercomputer calculations of a hypersonic flow past the model have been made. Supercomputer codes development of spatial modeling is one of the stages in a creation of hypersonic flight vehicle virtual model [1]. This virtual model has to provide physical description and modeling of a hypersonic direct-flow propulsion jet engine and a spatial flow past the model for flight velocities within Mach numbers $4 \leq M \leq 15$ and heights 20÷50 km. A need of the virtual model for hypersonic flight vehicle development is connected with essential technical difficulties and high material inputs on carrying out tests in ground wind tunnels and flight experiments, a difficult spatial structure of interacting among themselves and with boundary layer shock waves, and also with a difficulty of mathematical model that includes, in perspective, physic-chemical and radiation gas-dynamics processes. The purpose of this initial stage of work consisted in development of an effective gas-dynamic parallel supercomputer code and accomplishment of test calculations of the flow past the provided in publications hypersonic flight vehicle X−43.

2. Virtual model of a hypersonic flight vehicle

Virtual model of a hypersonic flight vehicle proposes to create spatial 3−D object model, to build unstructured numerical mesh around the model, to carry out calculations and to visualize results. A preparation of spatial 3−D model for a hypersonic flight vehicle is made by CAD systems and is described precisely in [2]. A surface of the model is rather complicated; it includes small radius of curves and sharp edges of adjacent surfaces. It is generally connected with large manual works to build regular mesh. An approach based on molecular dynamics [3] allowed avoiding losses due to automatic construction of unstructured meshes. The constructed unstructured mesh is converted into graph that is used for supercomputer modeling.

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3. Software platform for parallel calculations

The description of approaches of the organization of calculations for grid problems for parallel calculations is present in [4]. In this paper own approach which doesn't demand reorganization of logic of work and structures of data of the consecutive program is realized. Performance of a technological chain of work on a flow of objects of irregular shape requires carrying out the following preliminary operations:

1) Creation of a link graph between numerical cells.
2) Partitioning set of numerical cells into subareas. This step was carried out with use of a widespread open software package METIS.
3) Formation of the control data determinating calculations for each of numerical subareas.

The scheme of the organization of works in consecutive and parallel options of a code is presented in figure 1. One could see that in a cycle of calculation of a time step, a change come down to splitting calculations for "internal" and for "external" groups of cells, and also to a call of the subroutines (functions for C/C++) providing start of asynchronous compact operations of exchange and expectation of the end of operations. Additional operations are marked in red color. To provide universality of data exchange between areas the structures of sparse matrixes representation are used.

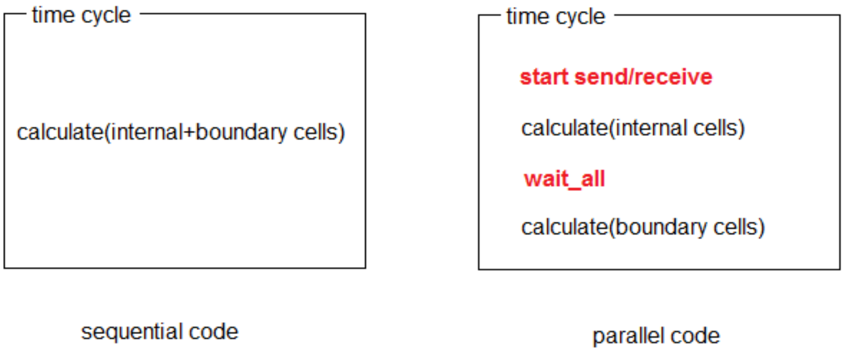

Figure 1. Sequential and parallel schemes of calculation flow**.**

The similar approach has been used earlier in the software platform INMOST [4].

As the existing tools of settlement grids are limited by value of about 30 million cells, that for receiving more detailed grids is used the subdivision method consisting in splitting each control volume into 8 smaller in such a way that splitting the next volumes are coordinated among themselves on the common side (figure 2). For each face splitting looks in such a way that the middle of the edges of a face connect, forming on each face four new triangles instead of previous one. So, if the middle of the edges of the triangle formed by tops 1, 2 and 3, to denote as 12, 13 and 23, then new triangles are (1, 12, 13), (12, 2, 23), (13, 23, 3) and (12, 13, 23). In a tetrahedron, unlike a boundary triangle, unique subdivision on smaller isn't present any more. Uniquely, however, the new tetrahedrons containing tops 1, 2, 3 and 4 are determined: (1, 12, 13, 14), (2, 12, 23, 24), (3, 13, 23, 34) and (4, 14, 24, 34). Other tetrahedrons can be set, for example, as (12, 34, 13, 14), (12, 34, 14, 24), (12, 34, 23, 13) and (12, 34, 23, 24).

By subdivision of each cell into 8 more small we succeed to build numerical meshes for hypersonic flight vehicle X–43 with about 240 million cells, 700 million cells and 2 billion cells.

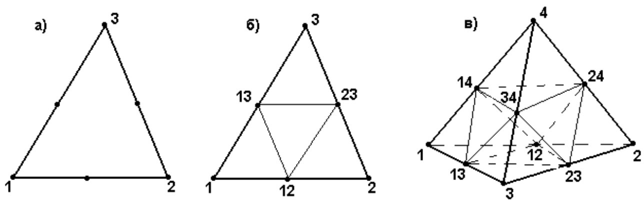

Figure 2. Triangle and tetrahedron partitioning schemes.

4. Region partitioning

The examples of spatial region partitioning for hypersonic flight vehicles X–43 and X–51, for 128 and 64 cuts correspondingly, are presented in figures 3, 4. The partitioning has been made by widespread open software METIS on PC at the preliminary preparation stage for supercomputer calculations. The RAM requirements at partitioning stage do not exceed requirements at other preliminary stages.

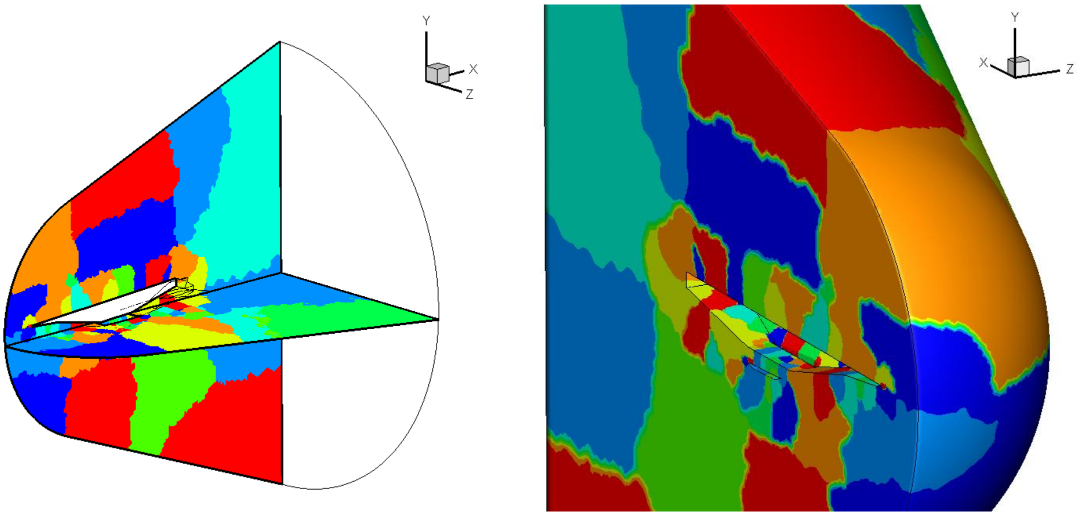

Figure 3. 128-cut partitioning of numerical region around X–43.

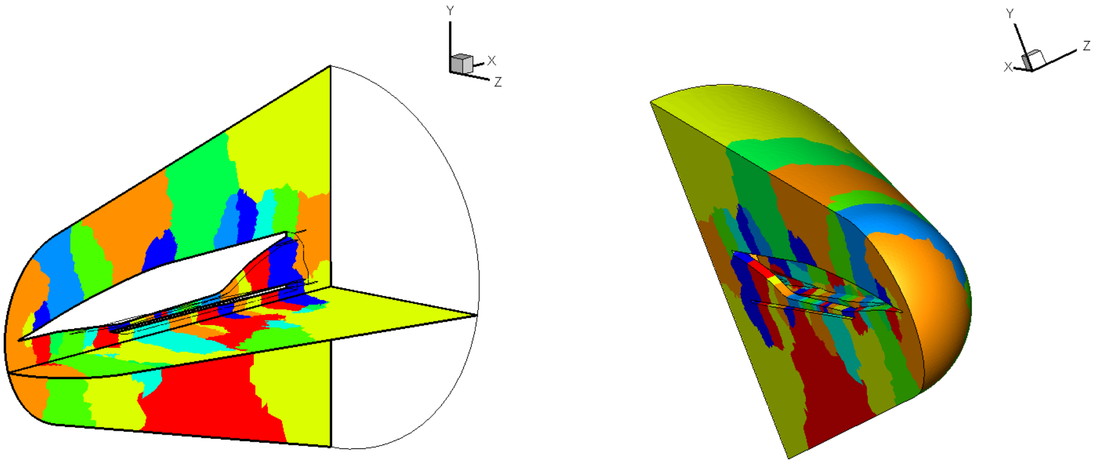

Figure 4. 64-cut partitioning of numerical region around X–51.

5. Supercomputing calculations

The sequential code ug3D was used to process it into parallel version. This code was recently used for a modeling of a hypersonic flow past a model objects in a hypersonic shock tube [5]. The ug3D code models gas flows on the base of the Navier-Stokes and the Euler equations for unstructured spatial meshes on the base of second order generalized S.K. Godunov's method.

The supercomputer calculations carried out for numerical mesh with 240 million cells. On 8 processors the typical calculation time for one time step is about 20 seconds and boundary cells exchange is about 1/20 second. The main additional preliminary processing was held outside parallel system, however it requires essential RAM amounts. The 240 million cells mesh is the maximum mesh for which we were able to check the correct working capacity of software platform. The efficiency of parallelization is above 89 % for up to 128 processor calculations. To build data structures at the preliminary stages for a mesh with 500 million cells a computer with more than 64 GB is needed, and for mesh with 2 billion cells – a computer with at least 256 GB RAM.

The figure 5 presents shock-wave high-resolution structure of the flow of the Mach number 6 past hypersonic flight vehicle X–43, pressure distribution in the symmetry plane, vehicle surface and few sections.

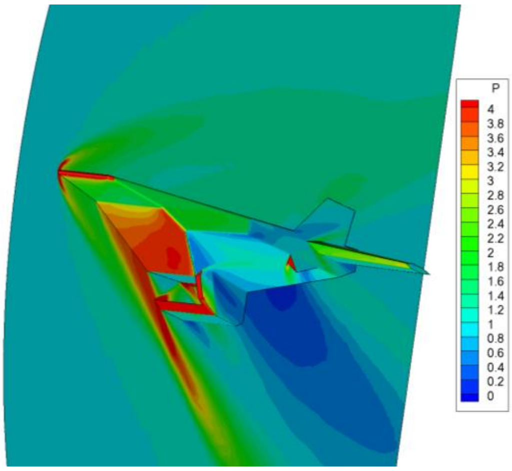

Figure 5. Pressure distribution in the symmetry plane and on the X–43 surface in a flow of the Mach number 6.

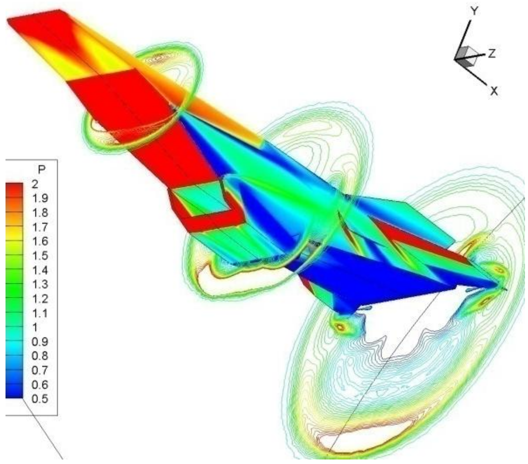

Figure 6. Pressure distribution on the X–43 surface and in some sections in a flow of the Mach number 6.

Combustion in propulsion jet engine has not been considered. The developed supercomputer code is the base for implementation of extended models of flows past hypersonic flight vehicles.

6. Conclusions

The software platform for numerical codes parallelization that does not require to rebuild the data structures and the nucleus of numerical part is described. The platform tools are applied for MPI-based parallelization for the Navier-Stokes (Euler) equations for spatial unstructured mesh calculations. The spatial unstructured meshes for hypersonic flight vehicle X–43 with up to 2 billion cells are built. Parallel code allows to carry out flow past hypersonic flight vehicle calculations with the Mach number 6 and higher and numerical meshes with up to 1 billion numerical cells and with up to 128 processors. The efficiency of parallelization is above 89 % for up to 128 processor calculations. Developed parallel code allows to carry out calculations with higher detailing in boundary layers and sharp gradient regions, to advance to conjugate simulations of integrated configuration and propulsion system, and also to implement optimization in the studied systems. The developed supercomputer code is also the base for implementation of extended models of flows past hypersonic flight vehicles.

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