V. SEREDA, M. AMBROZHEVICH

National Aerospace University «Kharkiv Aviation Institute», Ukraine

MASK GENERATOR FOR ORTHOGONAL REGULAR MESH

Existing mesh generators are focused mainly on obtaining non-orthogonal irregular grids designed to describe the curved boundaries of streamlined bodies. However, the thickening of the grid leads to an increase in the calculation time, and the non-conformity of the grid leads to unphysical effects. The software package (SP) developed by the authors for the simulation of gas-thermodynamic processes is oriented toward a much simpler description of the geometry, i. e., uses a different principle of increasing the smoothness of the solution in places with a complex surface structure. This principle consists in superimposing on the flow such sources of momentum and energy, which are equivalent in their effect on the flow to the interaction with the solid wall. SP contains a mask generator of an orthogonal regular grid. The initial data for building the mask is a 3D model created in any CAD application, which is saved in the STL format and placed in the project directory. Each cell contains information about the presence of a three-dimensional solid, the permeability of each face of the hexahedron, and the direction of the normal vector to the streamlined surface. In this regard, the generator creates three types of masks: volumetric, surface full and incomplete permeability, as well as a mask of guiding cosines. To obtain a volume (solid) mask from the center of each cell along the axes, a straight line is drawn and its intersection is checked with each triangle approximating the surface of the body under study. An odd number of intersections of triangles and a straight line indicates the presence of a volume mask in the cells. A surface impermeable mask is formed in three directions at the free cell section and the occupied volume mask. If it is necessary to introduce a semipermeable mask, its localization and measure are assigned by the user. The mask of the guiding cosines is assigned in the cell, which is adjacent to the surface impermeable mask. The values of the guiding cosines are assigned equal to the corresponding values of the nearby triangle approximating the surface of the 3D model. The generated masks are formed as separate files. A SolidWorks application has been developed that allows for volumetric visualization. In the decisive program, the information about the presence of the volume mask is used as follows: the volume mask is excluded from the solution area, self-similar problems are solved near the surface, and if there are guiding properties, an isentropic flow rotation is performed.

Keywords: computational grid; volume mask; surface mask; cosine mask.

Introduction

In modern conditions, the creation of new competitive models in the field of critical technologies based on outdated approaches is unproductive. And the use of standard gas-dynamic packages (Flow Works, ANSYS Fluent, etc.), which are widely used even among specialists, is unsuitable for modeling due to the specificity of the tasks. In this regard, self-respecting organizations that develop complex technological objects or are engaged in the training of specialists of the corresponding profile should independently provide themselves with an adequate modeling technology [1].

Often, developers of their own gas-dynamic packages are limited to creating only the crucial programs (the so-called "solvers"), using open grid generators (for example, gMesh, EasyMesh, etc.) and graphical interfaces (for example, Tech Plot 360, VisIt, etc.). However, adapting your own software algorithm to other people's modules deprives the first of its autonomy, significantly slows down and complicates the debugging of the "solver", and binds the developer to a specific version of the external application.

The well-known mesh generators [2-5] are mainly focused on the creation of non-conformal tetrahedral (TETRA), quadrangular (QUAD) or hexahedral (HEXA) grids with an irregular step. The use of such grids and a combination of various geometric types of elements (TETRA, QUAD, HEXA) is justified for approximating objects with curved borders [6-8]. However, if it is necessary to solve problems with moving boundaries, the logic of rebuilding such a grid on a new time layer is extremely complicated, which forces the developer to switch to more simple forms. In addition, manipulations to bring the "alien" grid into the form necessary for the developer seem to be unproductive.

Thus, the creation of a full-fledged software package (SP) that provides a closed loop modeling of an object of technology is impossible without an integrated grid generator and graphic module integrated into the software. This article presents an example of the grid generator implementation for SP, which uses proprie-

tary methods for solving the system of equations of gas dynamics and, accordingly, special types of masks are used.

Materials and Methods

Cell Structure Description. In the author's calculation complex [9, 10] S. K. Godunov's difference scheme is used for boundary nodes. The scheme is implemented on a hexahedral computational grid with a regular spatial step without using fractional or curvilinear cells in the Cartesian coordinate system. With this approach, questions related to the non-conservative nature of the pulse balance equation, the manifestation of unphysical grid effects [11], and the decrease in the time step according to the Courant-Friedrichs-Lewy condition are eliminated.

Three types of masks are used (see Fig. 1), which have the following purpose for displaying the corresponding effects. A surface mask (surface[NX][NY][NZ][3]) is used to reproduce "thin" partitions of zero thickness, with full or partial permeability between cells. The volume mask (volume[NX][NY][NZ]) is used to model the "solid" structural elements. To display the smooth nature of the guiding properties of curved surfaces in the model, a mask of guiding cosines is used (cosine[NX][NY][NZ][3]) [12].
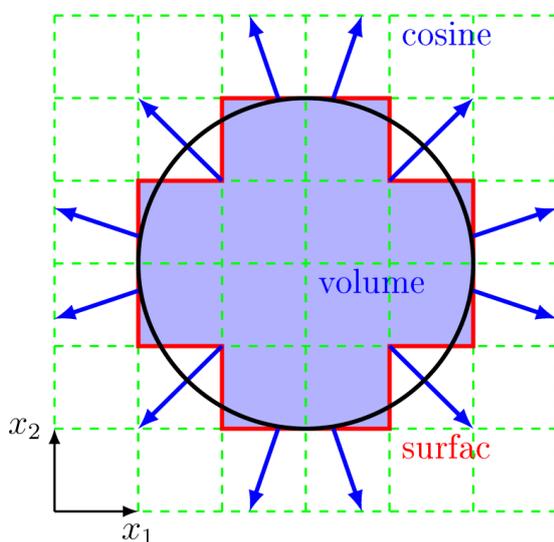

Fig. 1. Mask types for circle approximation
on orthogonal regular mesh

The initial data for masks generation is the geometrical model of the object under study, which can be obtained in any external CAD application. Due to the fact that today in the field of CAD applications (Solid-Works, Pro/ENGINEER, CATIA, AutoCAD, etc.), some progress has been achieved and sufficient inter-changeability, the development of our own integrated CAD module in the software seems to be impractical.

In most modern CAD applications, the main representation of the modeling object is, so-called boundary representation of figures – BREP [13]. In this case, a solid body is a set of interconnected surface elements – triangles, whose position in space is determined by an array of coordinates of the triangles vertices (vertex[NT][3]) and unit normals (normal[NT][3]) to them (see Fig. 2). Therefore, the geometry of the object under study can be obtained in any external CAD application, followed by saving in high quality STL format and ASCII encoding.
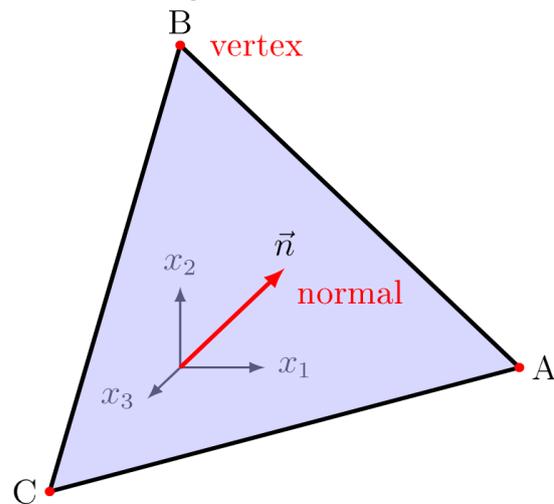

Fig. 2. BREP representation surface of objects
in CAD-systems

The grid generator is created independently in two programming languages C++ and FORTRAN in the standards C'11 and F'90, respectively. To visualize the created mesh, the WinBGIm graphic library is used, which is built into the development environment (Approximatrix Simply Fortran 2 and DevC++). Ready masks are saved as three text files (Solid.msh, Areal.msh, Cosin.msh) for subsequent import into the calculation module. For spatial visualization of masks, a separate application to SolidWorks design environment in the C# programming language has also been developed.

Mask Generation Algorithm. At the preparatory stages of the grid generator, the number of lines in the STL file determines the number of triangles NT that approximate the surface of the simulated object (see Fig. 3). Afterwards, arrays of coordinates of the vertices of the triangles (vertex[NT][3]) and normals to them (normal[NT][3]) can be declared. Arrays of the main masks (volume[NX][NY][NZ], surface[NX][NY][NZ][3], cosine[NX][NY][NZ][3]) are set according to user-defined dimensions of the computational domain (NX, NY, NZ). Next, the arrays filling is conducted according to the following algorithm.

Begin

Reading arrays from an STL file vertex[NT][3] and normal[NT][3]

Start cycles (1...NT) and (1...NX, 1...NY, 1...NZ)

Defining a ray from the center of each cell parallel to each axis

Finding the equation of a plane belonging to a triangle $\triangle ABC$

Determination the coordinate point O of the intersection beam and plane

Check that the point O belongs to the current triangle $\triangle ABC$ — no

yes

Volume mask filling volume[NX][NY][NZ]

Search for the nearest triangle $\triangle ABC$ to current volume mask — no

yes

Cosine mask filling cosine[NX][NY][NZ][3]

Check for the absence of a volume mask in the nearest cell — no

yes

Surface mask filling surfac[NX][NY][NZ][3]

Exit cycles (1...NT) and (1...NX, 1...NY, 1...NZ)

Visualization of generated masks editing results

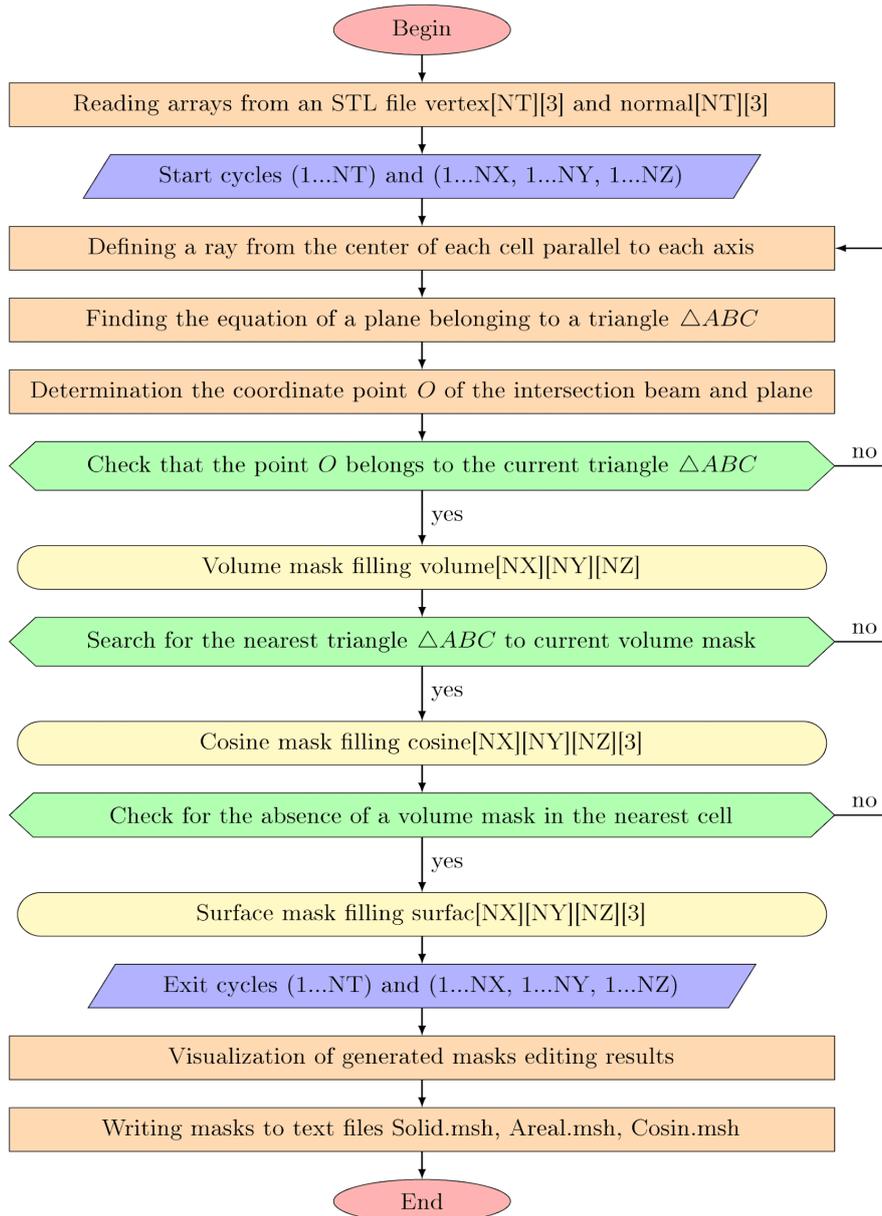Writing masks to text files Solid.msh, Areal.msh, Cosin.msh

End

Fig. 3. Block diagram of the mesh generation algorithm

When generating masks, the volumetric mask is primary, which subsequently determines the boundaries of the solid (surface mask) and the direction of the normal vector to it (cosine mask). To obtain a three-dimensional mask through the center of the current cell $D(x_3, y_3, z_3)$ and the next $E(x_4, y_4, z_4)$ a straight line DE, is drawn along each axis, the equation of which is given as:

$$\begin{cases} x = t(x_4 - x_3) + x_3; \\ y = t(y_4 - y_3) + y_3; \\ z = t(z_4 - z_3) + z_3. \end{cases} \quad (1)$$

Then, in turn, we consider the planes to which all NT triangles ΔABC belong, approximating the 3D model under consideration. By the known coordinates of the vertices at points $A(x_1, y_1, z_1)$, $B(x_2, y_2, z_2)$, $C(x_3, y_3, z_3)$, which are taken from the array vertex[NT][3], the equations of the planes are sequentially compiled:

$$\begin{aligned} &(x - x_1)[(y_2 - y_1)(z_3 - z_1) - (y_3 - y_1)(z_2 - z_1)] + \\ &+ (y - y_1)[(x_3 - x_1)(z_2 - z_1) - (x_2 - x_1)(z_3 - z_1)] + \quad (2) \\ &+ (z - z_1)[(x_2 - x_1)(y_3 - y_1) - (x_3 - x_1)(y_2 - y_1)] = 0. \end{aligned}$$

The joint solution of the system of equations (1) and (2) gives the coordinate of the point $O(x, y, z)$ of the intersection of the plane and the line. The fact that the point O belongs to the triangle ΔABC indicates its intersection with the line. An odd number of intersections [14-17] indicates the presence of a volume mask in the cell (see Fig. 4). In the section 2.3 shows an algorithm for determining whether a point belongs to a triangle.
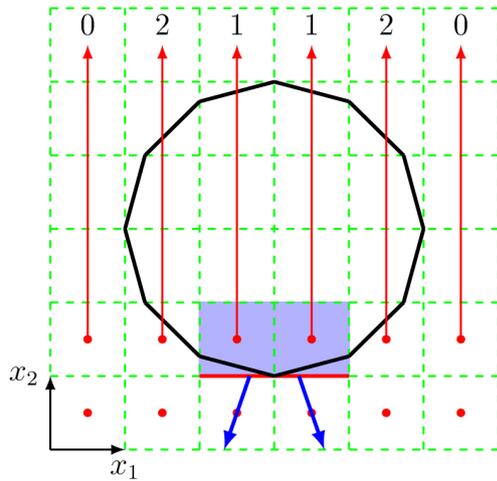
Fig. 4. Scheme for understanding location
of volume mask in cell

If a volume mask is present in cell number i, j, k, then a digit other than zero is written to the array volume[i][j][k]. If the three-dimensional mask displays solid objects, then the value "1" is assigned to the array. If features are placed in the cell, the value is assigned to the array, for example, "2". If a "reactive" mask is required to determine the integral parameters, then "3" is assigned to the array. In general, the values of the quantities are not important and can be any.

Then, at the interface between volume and free cells, an array of surface mask surface[NX][NY][NZ][3] is generated. The surface mask can simulate incomplete permeability of the wall, i. e. display holes in the wall smaller than the grid spacing.

Permeability in the range 0…1 is set by the user, with "0" denoting a fully permeable wall, and "1" – completely impervious. The value of the guide cosine mask cosine[i][j][k][3] is assigned to a free cell (i, j, k) near the surface mask if the plane of the triangle ΔABC approximating a solid is not parallel to the planes XOY, XOZ, YOZ.

The distance from the center of the cell adjacent to the surface mask to the nearby triangle is determined, and the corresponding cosine mask is assigned to the mask of the guiding cosines in this cell. The mask of guiding cosines is a set of cosines of the angles that the normal vector normal[NT][3] forms with positive coordinate axes.

When calculating a mask for thin-walled shells (for example, a jet engine shell), a similar algorithm is used, with the only difference being that the direction of the normal is taken with the opposite sign for cells inside a false volume mask. In this case, the volume mask is not used by the calculation module.

Algorithm Speed Comparison. Three methods were considered for determining whether the point O belongs to the triangle ΔABC. According to the first

(see Fig. 5), the sum of the areas S_1, S_2, S_3 of the triangles ΔCOB, ΔCOA and ΔBOA formed by the intersection point was compared O with vertices of the main triangle ΔABC and the area S_Σ of this triangle. Belonging to a point is determined by the equality:

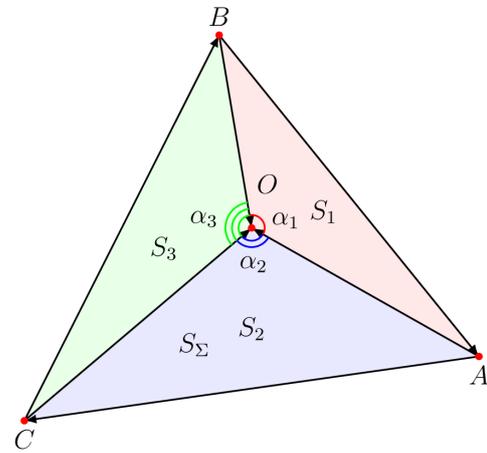$$S_1 + S_2 + S_3 = S_\Sigma . \tag{3}$$

Fig. 5. Scheme for understanding determination
of point belonging to arbitrary triangle

According to the second, compare the sum of the angles α_1, α_2, α_3 at the vertex O of the same triangles ΔCOB, ΔCOA and ΔBOA with a value of 360º. The fact that the point O belongs to the triangle ΔABC approximating the surface is determined by the equality:

$$\alpha_1 + \alpha_2 + \alpha_3 = 360° . \tag{4}$$

According to the third, the signs a, b and c of pairwise vector products $\overrightarrow{CB} \times \overrightarrow{CO}$, $\overrightarrow{BA} \times \overrightarrow{BO}$ and $\overrightarrow{AC} \times \overrightarrow{AO}$ of the triangle ΔABC and the vectors from the vertex to the point O, respectively. The affiliation of the point O is determined by the equality of one sign of all vector products:

$$(\alpha > 0 \wedge b > 0 \wedge c > 0) \vee (\alpha < 0 \wedge b < 0 \wedge c < 0) . \tag{5}$$

To compare the methods, we estimated the time to obtain a three-dimensional mask of a sphere whose surface is approximated by 6162 triangles. The most economical is the third method (see Table 1 – set off), which does not require the use of the resource-expensive functions sqrt() [18] and acos(). This algorithm is implemented in the current version of the software.

Comparison of two floating-point values (according to (3) and (4) with their inaccurate rounding can lead to incorrect results. Instead of using the equality operation, it is more rational to use a function that determines how close these two quantities are to each other (differ by a small amount of epsilon 10^{-6}). Therefore, the third method is characterized by higher accuracy and speed, because it defines the sign of the values.

Table 1

Comparison of time spent on obtaining volume mask using various methods

Applied method	Calculation time, s
Comparison of the sum of the areas of the triangles	100,171
Comparison of angles between segments	93,625
Definition of the sign of a vector work	31,969

Results

In the figure (see Fig. 6) shows the results of the software for a grid of 20×20×20 cells using an example of a sphere. The mask of cosines is displayed as a plane bounded by a cell, tangent to the initial surface of the 3D model and adjacent to the surface mask. The error in constructing the volume mask does not exceed the cell step.

Masks are imported into multi functional software for solving unsteady spatially heterogeneous problems of gas thermodynamics. The software includes a grid generator, a calculation module and a graphical interface. The entire software package is also independently implemented in C++ and Fortran.

In the figure (see Fig. 7) shows the working window of the grid generator when constructing a mask of an infinite cylinder in the computational domain with dimensions of 100×40 cells. In the enlarged area, the resulting masks are displayed: dark gray – volume, light yellow – surface, and light turquoise – guide cosines.

In the figure (see Fig. 8) presents a color map of the speed when calculating the external flow around the cylinder on a coarse orthogonal regular grid at a blowing speed of 30 m/s. An increase in the smoothness of the solution in the near-wall zones of the flows [19] on such a relatively coarse grid is achieved by using the method of singularities of the form of sources-sinks of momentum and energy.
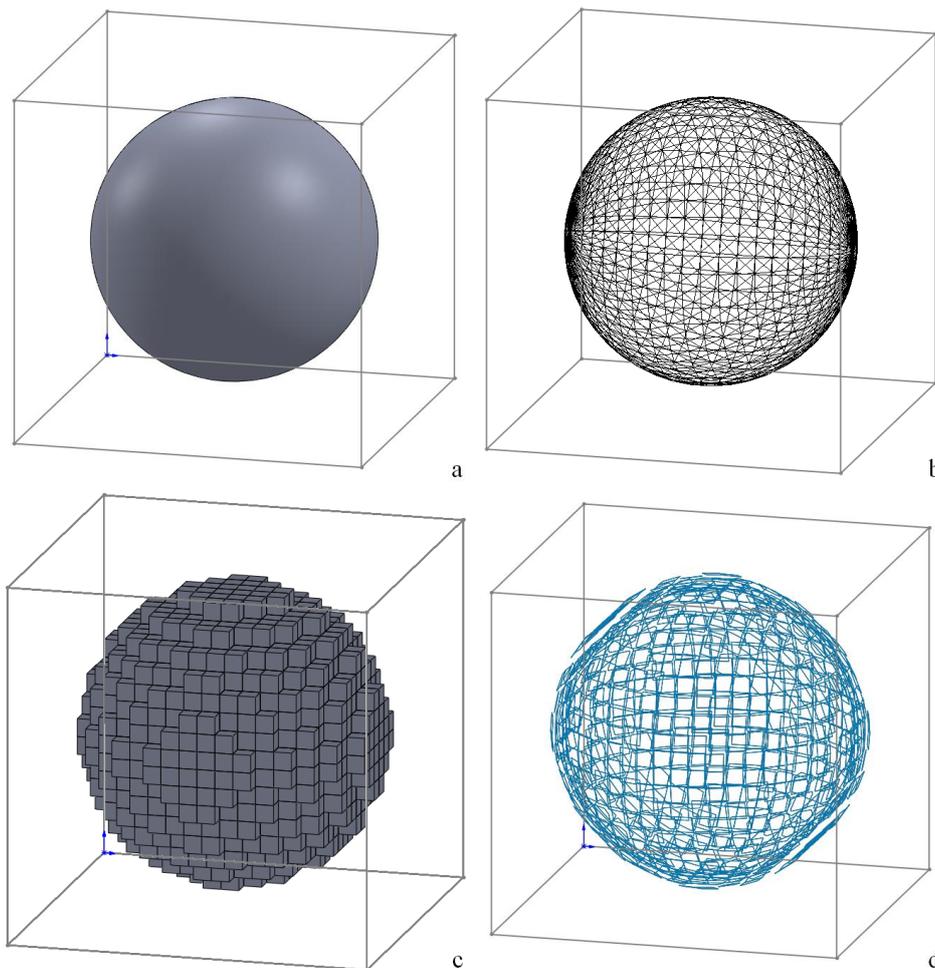

Fig. 6. Example of obtaining masks: a) initial geometric model of sphere; b) BREP representation of model in STL file; c) hexahedral mesh with volumetric and surface masks; d) mask of averaged normal surfaces
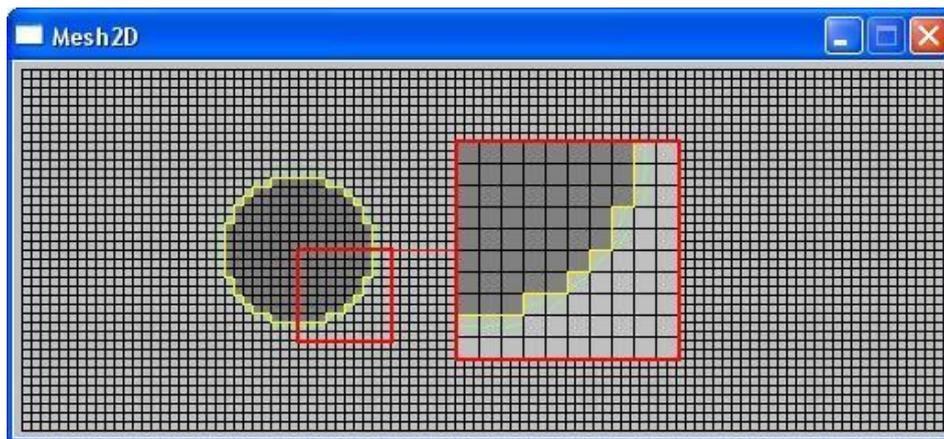
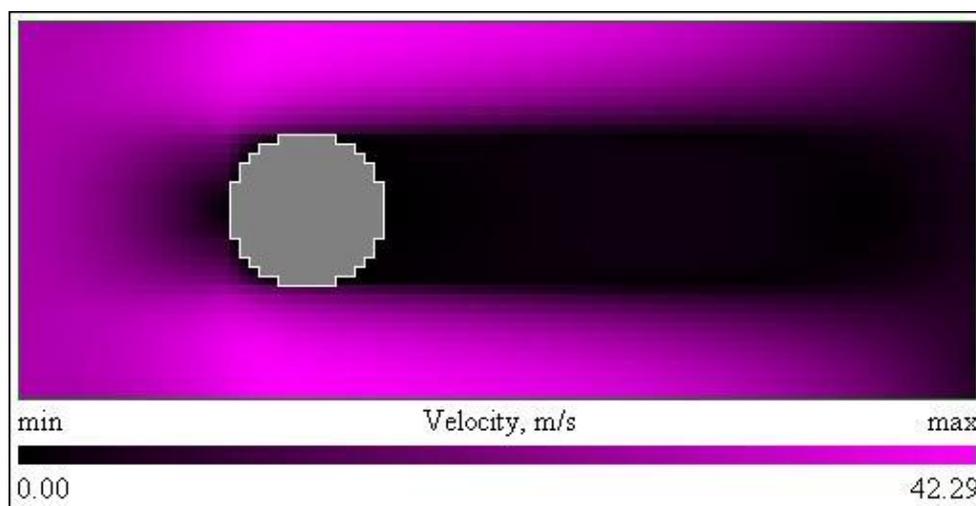Fig. 7. Example of generating computational grid of size 100×40

Fig. 8. Example of blowing endless cylinder at speed of 30 m/s

When simulating the flow, a cell with a volume mask value volume[i][j][k]=1 is excluded from the solution area of the boundary value problem. Near the surface mask surface[NX][NY][NZ][3]=1 the problem of gas interaction with the obstacle is solved.

If the value of the surface mask surface[NX][NY][NZ][3]=0…1 the problem of the decay of an arbitrary discontinuity and the interaction of the gas with the obstacle are simultaneously solved. In cells with the cosine mask cosine[i][j][k][3]≠0 an isentropic rotation of the flow is used (i. e. surface forces do not do work). However, a "percussion" rotation mechanism may be used depending on the dissipative signature of the physical original.

Conclusion

Existing mesh generators are focused mainly on obtaining non-orthogonal irregular grids designed to describe the curved boundaries of streamlined bodies. However, the thickening of the grid leads to an increase in the calculation time, and the non-conformity of the grid leads to unphysical effects. The software package developed by the authors uses a different principle of increasing the smoothness of the solution in places with a complex surface structure. This principle consists in superimposing on the flow such sources of momentum and energy, which are equivalent in their effect on the flow to the interaction with the solid wall.

The presented orthogonal regular grid generator allows you to speed up and simplify the construction of grids that can be effectively used in a CFD solver. The grid generator uses its own adaptive conformal algorithm for constructing specific masks. This algorithm generates volume and surface masks, as well a mask of guiding cosines in a Cartesian coordinate system. To build a mask, a geometric model is used, which is limited by the "closed" surface. To obtain a 3D model, any third-party CAD application can be used.

Calculations on a relatively coarse grid are eligible due to another method of describing the flow near the walls. The essence of this approach is that groups of features of the form of sources-sinks of momentum and energy are superimposed on the flow, which are equiva-

lent in their power to the interaction of the flow with a wall of complex geometry. The relative simplicity of the mask generation algorithm allows to reduce the labor costs of the software developer, which is an important factor in reducing the technical risk and the cost of research.

The modeling method cultivated by the authors [9, 12, 19], for which a generator of masks on a regular rectangular grid has been developed, in contrast to the MCO [10] and FEM [11] on unstructured grids, allows: use ordinary computers for modeling without using parallelization; display the characteristics of the internal flow of the medium with an accuracy of 10%; it is much easier and more economical to implement dynamic meshes; does not require changing the logic of the calculation near geometry of complex shape.

References (GOST 7.1:2006)

1. Tu, J. Computational Fluid Dynamics. CFD Mesh Generation: A practical Guideline [Text] / J. Tu, G.-H. Yeoh, C. Liu. – Oxford : Butterworth-Heinemann, 2018. – 601 p.

2. Geuzaine, C. Gmsh: a three-dimensional finite element mesh generator with built-in pre- and post-processing facilities [Text] / C. Geuzaine, J.-F. Remacl // International Journal for Numerical Methods in Engineering. – 2009. – Vol. 79 (11). – P. 1309-1331.

3. High Quality Surface Remeshing Using Harmonic Maps [Text] / J.-F. Remacle, C. Geuzaine, G. Compere, E. Marchandise // International Journal for Numerical Methods in Engineering. – 2009. – Vol. 83 (4). – P. 403-425.

4. RINGMesh: A programming library for developing mesh-based geomodeling applications [Text] / J. Pellerin, A. Botella, F. Bonneau, A. Mazuyer // Computers & Geosciences. – 2017. – Vol. 104. – P. 93-100.

5. An Open-Source Mesh Generation Platform for Biophysical Modeling Using Realistic Cellular Geometries [Text] / C. T. Lee, J. G. Laughlin, J. B. Moody, R. E. Amaro, J. A. McCammon, M. Holst, P. Rangamani // Biophysical Journal. – 2020. – Vol. 118 (5). – P. 1003-1008.

6. Persson, P.-O. A Simple Mesh Generator in MATLAB [Text] / P.-O. Persson, G. Strang // Society for Industrial and Applied Mathematics. – 2004. – Vol. 46 (2). – P. 329-345.

7. Ozkan, M. A Cartesian Based Mesh Generator With Body Fitted Boundary Layers [Text] / M. Ozkan, M. H. Aksel, O. U. Baran // 9-th Ankara International Aerospace Conference, 20-22 September 2017, METU, Ankara Turkey. – P. 1-8.

8. Prismatic Mesh Generation using Minimum Distance Fields [Text] / B. Roget, J. Sitaraman, Lakshminarayan, A. Wissink // Tenth International Conference on Computational Fluid Dynamics, 9-13 July 2018, Barcelona, Spain. – P. 1-27.

9. Амброжевич, М. В. Концепция проектирования компактной системы минометного старта летательного аппарата [Текст] / М. В. Амброжевич, В. А. Середа // Наука и техника Воздушных Сил Вооруженных Сил Украины. – 2016. – № 3 (24). – С. 74-79.

10. LeVeque, R. J. Finite-Volume Methods for Hyperbolic Problems [Text] / R. J. LeVeque. – Cambridge University Press, 2004. – 558 p.

11. Зубанов, В. М. Исследование влияния параметров сетки и моделей турбулентности на результаты CFD-расчетов плоских турбинных решеток [Текст] / В. М. Зубанов, А. В. Кривцов, А. А. Штрауб // Вестник Самарского государственного аэрокосмического университета им. академика С. П. Королёва (Национального Исследовательского Университета). – 2012. – № 3 (34). – С. 185-191.

12. Малоресурсный метод численного моделирования течений в геометрических областях сложной формы [Текст] / А. В. Амброжевич, И. П. Бойчук, С. Н. Ларьков, В. А. Середа // Авиационно-космическая техника и технология. – 2008. – № 6 (53). – С. 5-53.

13. Mantyla, M. An Introduction to Solid Modelling [Text] / M. Mantyla. – Rockville : Computer Science Press, 1988. – 401 p.

14. Badouel, D. An E_cient Ray-Polygon Intersection [Text] / D. Badouel // Graphics Gems (Academic Press Inc.). – 1990. – Vol. I. – P. 390-393.

15. Haines, E. Point in Polygon Strategies [Text] / E. Haines // Graphics Gems (Academic Press Inc.). – 1994. – Vol. IV. – P. 24-46.

16. Arenberg, J. Re. Ray / Triangle Intersection with Barycentric Coordinates [Electronic resource] / J. Re. Arenberg, R. Bogart // Ray Tracing News. – 1998. – Vol. 11, No. 1. – Access mode: http://graphics.stanford.edu/pub/Graphics/RTNews/html/rtnews5b.html#art3. – 10.10.2020.

17. Segura, R. J. Algorithms to Test Ray-Triangle Intersection. Comparative Study [Text] / R. J. Segura, F. R. Feito // Journal of WSCG. – 2001. – Vol. 9 (3). – P. 76-81.

18. Lamont, C. Fast Inverse Square Root [Electronic resource] / C. Lamont. – Purdue University, Indiana, 2003. – Access mode: http://www.lomont.org/papers/2003/InvSqrt.pdf. – 10.10.2020.

19. Амброжевич, М. В. Малоресурсная подмодель турбореактивного двигателя [Текст] / М. В. Амброжевич, А. В. Корнев, В. А. Середа // Авиационно-космическая техника и технология. – 2016. – № 1 (124). – С. 44-52.

References (BSI)

1. Tu, J., Yeoh, G.-H., Liu, C. Computational Fluid Dynamics. CFD Mesh Generation: A practical Guideline. Oxford, Butterworth-Heinemann Publ., 2018. 601 p.

2. Geuzaine, C., Remacle, J.-F. Gmsh: a three-dimensional finite element mesh generator with built-in pre- and post-processing facilities. International Journal

for Numerical Methods in Engineering, 2009, vol. 79 (11), pp. 1309-1331.

3. Remacle, J.-F., Geuzaine, C., Compere, G., Marchandise, E. High Quality Surface Remeshing Using Harmonic Maps. *International Journal for Numerical Methods in Engineering*, 2009, vol. 83 (4), pp. 403-425.

4. Pellerin, J., Botella, A., Bonneau, F., Mazuyer, A. RINGMesh: A programming library for developing mesh-based geomodeling applications. *Computers & Geosciences*, 2017, vol. 104, pp. 93-100.

5. Lee, C. T., Laughlin, J. G., Moody, J. B., Amaro, R. E., McCammon, J. A., Holst, M., Rangamani, P. An Open-Source Mesh Generation Platform for Biophysical Modeling Using Realistic Cellular Geometries. *Biophysical Journal*, 2020, vol. 118 (5), pp. 1003-1008.

6. Persson, P.-O., Strang, G. A Simple Mesh Generator in MATLAB. *Society for Industrial and Applied Mathematics*, 2004, vol. 46 (2), pp. 329-345.

7. Ozkan, M., Aksel, M. H., Baran, O. U. A Cartesian Based Mesh Generator With Body Fitted Boundary Layers. *9-th Ankara International Aerospace Conference*, 2017, METU, Ankara Turkey, pp. 1-8.

8. Roget, B., Sitaraman, J., Lakshminarayan, Wissink, A. Prismatic Mesh Generation using Minimum Distance Fields. *Tenth International Conference on Computational Fluid Dynamics*, 2018, Barcelona, Spain, pp. 1-27.

9. Ambrozhevich, A. V., Sereda V. A. *Kontseptsiya proyektirovaniya kompaktnoy sistemy minometnogo starta letatel'nogo apparata* [Design concept of a compact aircraft mortar launch system], *Science and Technology of the Air Force of Ukraine*, 2016, vol. 3 (24), pp. 74-79.

10. LeVeque, R. J. *Finite-Volume Methods for Hyperbolic Problems*. Cambridge, Cambridge University Press Publ., 2004. 558 p.

11. Zubanov, V. M., Krivtsov, A. V., Shtraub, A. A. *Issledovaniye vliyaniya parametrov setki i modeley turbulentnosti na rezul'taty CFD-raschetov ploskikh turbinnykh reshetok* [Investigation of the influence of grid parameters and turbulence models on the results of CFD calculations of plane turbine gratings]. *Bulletin of Samara State Aerospace University*, 2012, vol. 3 (34), pp. 185-191.

12. Ambrozhevich, A. V., Boychuk, I. P., Lar'kov, S. N., Sereda, V. A. *Maloresursnyy metod chislennogo modelirovaniya techeniy v geometricheskikh oblastyakh slozhnoy formy* [Low-resource method for numerical simulation of flows in geometric regions of complex shape]. *Aviacijno-kosmicna tehnika i tehnologia – Aerospace technic and technology*, 2008, vol. 6 (53), pp. 5-10.

13. Mantyla, M. *An Introduction to Solid Modelling*. Rockville, Computer Science Press Publ., 1988. 401 p.

14. Badouel, D. *An E_cient Ray-Polygon Intersection.* Graphics Gems, Academic Press Inc. Publ., 1990, vol. I, pp. 390-393.

15. Haines, E. *Point in Polygon Strategies*. Graphics Gems, Academic Press Inc. Publ., 1994, vol. IV, pp. 24-46.

16. Arenberg, J. Re., Bogart, R. Ray / Triangle Intersection with Barycentric Coordinates. *Ray Tracing News*, 1998, vol. 11, no. 1. Available at: http://graphics.stanford.edu/pub/Graphics/RTNews/ html/rtnews5b.html#art3 (accessed 10.10.2020).

17. Segura, R. J., Feito, F. R. Algorithms to Test Ray-Triangle Intersection. Comparative Study. *Journal of WSCG*, 2001, vol. 9 (3), pp. 76-81.

18. Lamont, C. *Fast Inverse Square Root*. Indiana, Purdue University, 2003. 12 p. Available at: http://www.matrix67.com/data/InvSqrt.pdf/ (accessed 10.10.2020).

19. Ambrozhevich, M. V., Kornev, A. V., Sereda, V. A. *Maloresursnaya podmodel' turboreaktivnogo dvigatelya* [Low-resource submodel of a turbojet engine]. *Aviacijno-kosmicna tehnika i tehnologia – Aerospace technic and technology*, 2016, vol. 1 (124), pp. 44-52.

ГЕНЕРАТОР МАСОК ДЛЯ РЕГУЛЯРНОЇ ОРТОГОНАЛЬНОЇ СІТКИ

В. О. Середа, М. В. Амброжевич

Існуючі генератори сіток орієнтовані в основному на отримання неортогональних нерегулярних сіток, призначених для опису криволінійними межами обтічних тіл. Однак згущення сітки призводить до збільшення часу розрахунків, а неконформність сітки – до нефізичних ефектів. Розроблений авторами пакет програм (ПП) для моделювання газотермодинамічних процесів орієнтований на істотно більш простий опис геометрії, через те що використовує інший принцип підвищення гладкості рішення в місцях зі складною структурою поверхні. Цей принцип полягає в накладенні на потік таких джерел імпульсу і енергії, які еквівалентні за своїм впливом на потік взаємодії з твердою стінкою. ПП містить масковий генератор ортогональної регулярної сітки. Вихідними даними для побудови маски є створена в будь-якому CAD-додатку 3D-модель, яка зберігається в форматі STL і розміщується в каталозі проекту. Кожна комірка містить в собі інформацію про наявність тривимірного твердого тіла, проникності кожної грані гексаедру й напрямок вектора нормалі до обтічної поверхні. У зв'язку з цим генератор створює три типи масок: об'ємну, поверхневу повної і неповної проникності, а також маску напрямних косинусів. Для отримання об'ємної (тілесної) маски з центру кожної комірки уздовж осей проводиться пряма і перевіряється її перетин з кожним трикутником, що апроксимує поверхню досліджуваного тіла. Парна кількість перетинань трикутників і прямої свідчить про наявність у комірці об'ємної маски. Поверхнева непроникна маска формується в трьох напрямках

на розділі вільної комірки зайнятої об'ємної маскою. При необхідності введення напівпроникною маски її локалізація і міра призначається користувачем. Маска напрямних косинусів призначається в комірці, яка примикає до поверхневої непроникної маски. Значення напрямних косинусів присвоюються рівними відповідним значенням довколишнього трикутника, що апроксимує поверхню 3D-моделі. Згенеровані маски формуються у вигляді окремих файлів. Розроблено додаток для середовища SolidWorks, що дозволяє виконувати об'ємну візалізацію. У вирішувальній програмі інформація про наявність об'ємної маски використовується наступним чином: об'ємна маска виключається з області рішення, поблизу поверхневої вирішуються автомодельні завдання, а при наявності напрямних властивостей – проводиться ізоентропічний поворот потоку.

Ключові слова: розрахункова сітка; об'ємна маска; поверхнева маска; маска косинусів.

ГЕНЕРАТОР МАСОК ДЛЯ РЕГУЛЯРНОЙ ОРТОГОНАЛЬНОЙ СЕТКИ
В. А. Середа, М. В. Амброжевич

Существующие генераторы сеток ориентированы в основном на получение неортогональных нерегулярных сеток, предназначенных для описания криволинейными границами обтекаемых тел. Однако сгущение сетки приводит к увеличению времени расчетов, а неконформность сетки – к нефизичным эффектам. Разработанный авторами пакет программ (ПП) для моделирования газотермодинамических процессов ориентирован на существенно более простое описание геометрии, т. к. использует иной принцип повышения гладкости решения в местах со сложной структурой поверхности. Этот принцип заключается в наложении на поток таких источников импульса и энергии, которые эквивалентны по своему воздействию на поток взаимодействию с твердой стенкой. ПП содержит масочный генератор ортогональной регулярной сетки. Исходными данными для построения масок является созданная в любом CAD-приложении 3D-модель, которая сохраняется в формате STL и помещается в каталог проекта. Каждая ячейка содержит в себе информацию о наличии трехмерного твердого тела, проницаемости каждой грани гексаэдра и направление вектора нормали к обтекаемой поверхности. В связи с этим генератор создает три типа масок: объемную, поверхностную полной и неполной проницаемости, а также маску направляющих косинусов. Для получения объемной (телесной) маски из центра каждой ячейки вдоль осей проводится прямая и проверяется ее пересечение с каждым треугольником, аппроксимирующим поверхность исследуемого тела. Нечетное количество пересечений треугольников и прямой свидетельствует о наличии в ячейки объемной маски. Поверхностная непроницаемая маска формируется в трех направлениях на разделе свободной ячейки занятой объемной маской. При необходимости введения полупроницаемой маски ее локализация и мера назначается пользователем. Маска направляющих косинусов назначается в ячейке, которая примыкает к поверхностной непроницаемой маске. Значения направляющих косинусов присваиваются равными соответствующим значениям близлежащего треугольника, аппроксимирующего поверхность 3D-модели. Сгенерированные маски формируются в виде отдельных файлов. Разработано приложение для среды SolidWorks, позволяющее выполнять объемную визуализацию. В решающей программе информация о наличии объемной маски используется следующим образом: объемная маска исключается из области решения, вблизи поверхностной решаются автомодельные задачи, а при наличии направляющих свойств – производится изоэнтропический поворот потока.

Ключевые слова: расчетная сетка; объемная маска; поверхностная маска; маска косинусов.

Середа Владислав Александрович – д-р техн. наук, доцент кафедры конструкций и проектирования ракетной техники, Национальный аэрокосмический университет им. Н. Е. Жуковского «Харьковский авиационный институт», Харьков, Украина.

Амброжевич Майя Владимировна – канд. техн. наук, доцент, доцент кафедры аэрокосмической теплотехники, Национальный аэрокосмический университет им. Н. Е. Жуковского «Харьковский авиационный институт», Харьков, Украина.

Vladislav Sereda – ScD Engineering, Associate Professor of the Department of Rocket Design and Engineering, National Aerospace University "Kharkov Aviation Institute", Kharkov, Ukraine,
e-mail: v.sereda@khai.edu, ORCID: 0000-0001-5687-4282, Scopus Author ID: 57193732804,
ResearcherID: W-1604-2018, https://scholar.google.com.ua/citations?user=_8SuEN0AAAAJ&hl=uk

Maya Ambrozhevich – PhD Engineering, Docent, Associate Professor of the Department of Aerospace Heat Engineering, National Aerospace University "Kharkov Aviation Institute", Kharkov, Ukraine,
e-mail: m.ambrozhevich@khai.edu, ORCID: 0000-0003-0856-8234, Scopus Author ID: 00000000000,
ResearcherID: W-0000-0000.