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Modelling of the Bagular Aneurysms of the Wall of The Blood Vessel Taking Into Account the Rheological Properties of the Blood

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Abstract—The article presents some results of the modeling of the bag-like aneurysm by the finite element method. The model takes into account the specificity of the blood flow from the point of view of various rheological models, as well as a significant change in the shape of the saccular aneurysm depending on pressure.

Keywords—Aneurysm, CAE, modelling, rheological

I. INTRODUCTION

According to the existing views, aneurysm of the vessel is a chronic degenerative dystrophic disease, consisting in a significant expansion of the artery or, more rarely, veins in the form of a limited protrusion of the blood vessel wall or its even stretching in a certain area.

True arterial aneurysm develops mainly under the influence of pathological changes that have arisen in the vessel wall, and only occasionally due to erosion and injury. The modified (thinned) wall of the artery cannot withstand the pressure of the blood and gradually stretches and bulges. Aneurysms arise and develop gradually over several years. Pathological process is not accompanied by special symptoms, especially at the beginning. In the later stages of aneurysm development, its symptoms can be severe: rupture of the vessel, its dissection, thrombosis, embolism (blockage), compression or destruction of adjacent tissues, organs, etc.

Depending on the shape, there are bagular (Fig. 1) and diffuse (Fig. 2) aneurysms. Sack-like aneurysmal formations are the most common, and diffuse enlargement of the artery is much less common for a considerable distance. Bag-shaped aneurysms are single and multiple, single or multi-chamber, ranging in size from a few millimeters to an adult's head.

The size of the aneurysm depends on the caliber of the affected vessel, the degree and nature of changes in its wall, the duration of the aneurysmal pathological process.

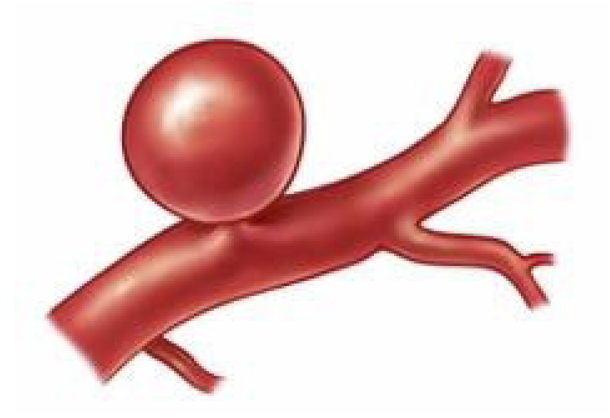

Fig. 1. Bagular aneurysm.

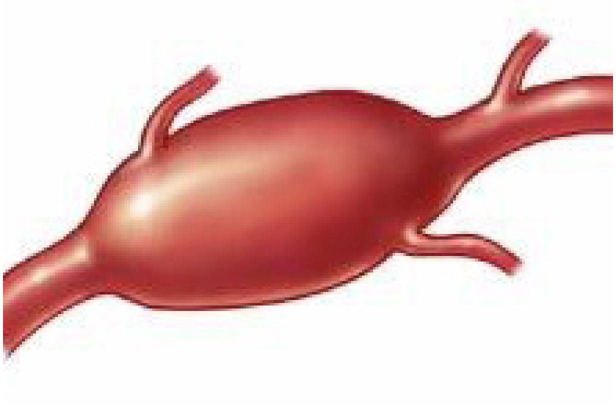

Fig. 2. Diffuse aneurysm.

With local expansion of the vessel in the affected area increases the cross-sectional area with, as a rule, a decrease in the strength of the vessel wall due to its thinning. Increased cross-sectional area leads to a local increase in pressure, thus forming positive feedback. Increased pressure leads to expansion of the vessel, and expansion - to an increase in pressure and in the future - to rupture of the wall.

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jerks, as a result of which a situation may arise in which the frequency of the pulsation of the blood flow will be close to the natural frequency of the bag-shaped cavity, which can be regarded as a membrane, which is fraught with resonant oscillations and destruction of the vessel.

Diagnosis of aneurysm is performed by ultrasound imaging, x-ray computer contrast or magnetic resonance imaging. However, to obtain a complete picture of the possible consequences of detecting an aneurysm in a patient, assessing the degree of criticality of aneurysmal formation, it is advisable to simulate the affected vascular area and identify the degree of "neglect" of the aneurysm, to make a forecast for the development of this pathological process. This analysis is based on complex model studies of the stress-strain state of an artery with an aneurysm while simulating blood flow in the vessel.

II. Formulation of the problem

It is known from [1] that the problems of biomechanics for bodies of complex shape and heterogeneous structure, such as blood vessels with blood pulsing in it, burdened with an aneurysm, are most often solved using numerical mesh methods, in particular, using the finite element method. The artery-bloodstream system is characterized by the interaction of blood flow on the one hand, and the elastic walls of an arterial vessel with a complex geometry on the other. The need to take into account in the aneurysm model the mechanisms and conditions for the interaction and interaction of elastic solids — blood vessel walls and flowing fluid — blood flow reduces this task to a class of multidisciplinary multiphysics tasks requiring simultaneous model reconstruction of various physical phenomena taking into account their interaction with each other.

Consequently, this task belongs to the class of FSI (Fluid Structure Interaction) [2] class of tasks — the interaction of elastic solids and fluid flows, which is one of the complex multidisciplinary tasks that require simultaneous coupled modelling of various physical phenomena, taking into account their mutual influence on each other . Most often, such problems, as is known from [2, 3, 4], are most effectively solved by finite element modelling tools, such as COMSOL Multiphysics [3] or ANSYS [2, 4].

The complexity of the solution and the realism of the solutions obtained depend on the overall goal of the research, the dimension of the problem, the accepted assumptions and the chosen methods of solution. Thus, the problem under study can be considered in a quasistationary (with a steady state) and non-stationary formulation. It is possible to organize the simultaneous calculation of the mutual influence of hydrodynamics and strength (coupled, two-way coupled) and independent, based on the assumption that fluid flow (blood flow) does not significantly change the shape of an elastic solid (segregated or one-way coupled) - a blood vessel. The quality and speed of calculations depends on the calculation systems used, the means of numerical finite element modelling, the degree of preparation and detail of mathematical model descriptions of interacting objects and continua.

III. Methodology

Before proceeding to the description of the process of building a model and experimenting with it, we introduce the following basic assumptions [1,5]:

1). The blood vessel and aneurysm are three-dimensional bodies.

eight). The dome of the aneurysm is axisymmetric and has a spherical shape.

2). The base of the aneurysm is rigidly fixed in the blood vessel.

3). The geometrical dimensions of the aneurysm and the internal pressure of the blood in it are considered in the physiological range.

4). Blood is an incompressible fluid that has certain viscosity properties.

5). The walls of arterial vessels are a complex multi-layer structure with characteristic parameters of strength and anisotropy of properties.

The general scheme for modeling aneurysm of an artery includes the following steps:

Step 1. The construction of the geometry of the object of research - in this case it is a section of a blood vessel with a bag-shaped aneurysmal formation.

Step.2. The task of the rheological properties of blood. It is necessary, first of all, to decide what kind of formal description sets the viscosity of the blood.

Step 3. Determination of the properties of the blood vessel walls, mainly the elastic properties and structural isotropy / anisotropy.

Step 4. The choice of the initial situation for the simulation, i.e. the establishment of the basic model characteristics of the object under study is the size of the simulated portion of the vessel with the aneurysm, the pressure of the blood in the vessel, the method of its fixation, etc.

Step 5. Building a finite element model of an aneurysm vessel.

Step 6. Formation of a scheme for solving a multiphysical problem of modelling a bag-shaped aneurysm.

Let us consider in more detail the implementation of these steps with an example.

As the initial real object of modelling we choose a straight section of a blood vessel with a caliber D = 5 ... 20 mm, a limited length L = (3 ... 5) ... (15 ... 80) mm, a wall thickness h = 0.5 ... 2.0 mm with a bag-shaped sphere-like aneurysm with diameter A = (1 ... 2) ... (5 ... 40) mm, offset from the vessel axis by S = (1 ... 2) ... (7.5 ... 30) mm.

Step 1. A geometric model of such a vessel with an axisymmetric spheroidal aneurysm in projection on the XZ plane has the form of a horizontal cylinder (the center of symmetry coincides with the origin of the coordinate system) and shifted along the vertical axis of the sphere - see fig. 3. Three-dimensional mapping of this model is presented in fig. 4.

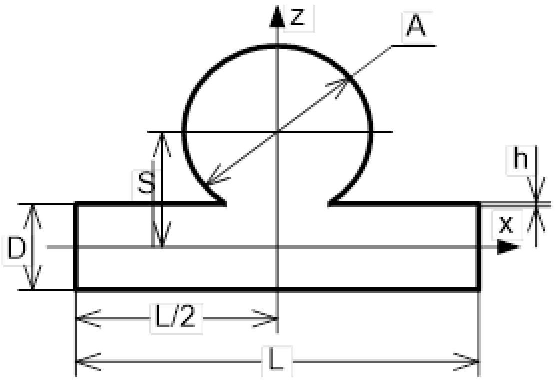

Fig.3. Geometric model of an aneurysm vessel in the xz plane.

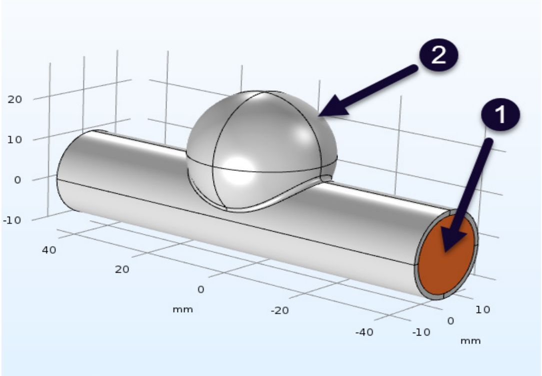

Fig. 4. Three-dimensional model (1 - blood, 2 - a vessel with an aneurysm)

Step 2. There are a number of models that describe the properties of blood. The most popular is the Newtonian model [6], according to which blood is an incompressible fluid, the viscosity coefficient of which depends only on its nature and temperature and does not depend on the conditions of the flow of the fluid, i.e.

$$\eta = \text{const}, \qquad (1)$$

however, the normal blood density is ρa = 1052…1062 Kg·м3, and its viscosity η = 0,005 Pa·c.

This formal description is suitable for relatively fast blood flow, but does not take into account the specificity of the behaviour of blood at low speeds of its flow, and this is especially important, in particular, when studying the possibility of carrying out stenting of the coronary vessels of the heart.

Non-Newtonian (or, more precisely, generalized Newtonian) models take into account the dynamics of changes in blood viscosity depending on the changing shear force, which is especially important at low blood flow rates. Among these models, one of the most famous is the Carro-Yashid model (Carreau-Yasuda model) [6,7], which reflects the non-linear dependence of dynamic viscosity on shear rate [8,9] and looks like:

$$\eta(\gamma) = \eta_\infty + (\eta_0 - \eta_\infty)[1 + (\lambda\gamma)^\alpha]^{\frac{(n-1)}{\propto}} \qquad (2)$$

where λ, α, n – constants determined experimentally, in this paper we use constants taken from the work [7]: λ = 46,53 c; α = 0,5; n = 0,342; η0 = 0,15 Pa·c и η∞ = 0,0035 Pa·c.

Note that the Carro-Yashid model describes blood as a non-Newtonian fluid between two limit Newtonian states — at infinitely small and infinitely large shear rates — with asymptotic viscosities η0 and η∞, accordingly [10]. It should also be noted that this model representation is in good agreement with the experimental data presented in [8,9].

A comparative analysis of the calculation results for the Newtonian and non-Newtonian models, carried out in [10], shows that the Carro-Yashid model gives about 10% higher tensile stresses in the walls of blood vessels, which makes it possible to recommend this model as preferred, significant fluctuations in blood flow velocity are expected.

Step 3. From numerous clinical studies [11] it is known that blood vessels (arteries and arterioles) can be represented in the form of a multilayer cylindrical shell. Most often, three layers (three shells) are distinguished in the walls of the artery - the inner layer (consists of a layer of endothelial elastin cells located on the connective layer), medium (elastic tissue and smooth muscle fibers - this is the thickest layer and it “controls” the changes in diameter arteries) and external (consists of collagen connective tissue). An arteriole differs from an artery in that its wall has only one layer of muscle cells, due to which it performs a regulatory function.

The mechanical behavior of the blood vessel wall depends on its structural components. With low internal blood pressure, the main role is played by elastin fibers of the inner layer, with high-collagen fibers of the outer layer, with physiological - both components.

For the case under consideration, we assume that the material of the blood vessel wall is isotropic with Young’s modulus E = 500 MPa, Poisson’s ratio μ = 0,4 and density ρc = 1378 Kg·m3.

Step 4. To conduct model experiments, it is necessary to determine the initial situation, i.e. set the dimensions of the model area of a blood vessel with a bag-shaped sphere-like aneurysm, choose a scheme for fixing the vessel in the body, establish the initial value of the initial blood pressure in the vessel. Let the area of the artery with an aneurysm spheroid formation is characterized by the following dimensions: length L = 80 мм, diameter D = 20 мм, wall thickness h = 1,5 мм, aneurysm diameter A = 40 мм, offset relative to the axis of the vessel aneurysm S = 24 мм. Let us assume that the blood pressure in the artery is changed from 80 Hg mm (10665 Pa) to 120 Hg mm (15998 Pa), the edges of the blood vessel have a fixed anchorage, the rest of the vessel has no support and the gravity is 0 (i.e. we assume that the simulated blood vessel with blood circulating in it has no weight).

Step 5. After the geometrical model of the object under study is constructed, we will create its finite element (discrete) model, i.e. on the area of space occupied by the object, we will apply a grid of nodes and elements. Usually the area is divided into more finite elements of relatively simple form, interconnected in nodes. The elements have common nodal points and together approximate the shape of the area.

We will construct a finite-element model of an artery with an aneurysmal formation by splitting the dome of the aneurysm and the cylinder of the vessel into shell elements of a triangular shape (Fig. 5).

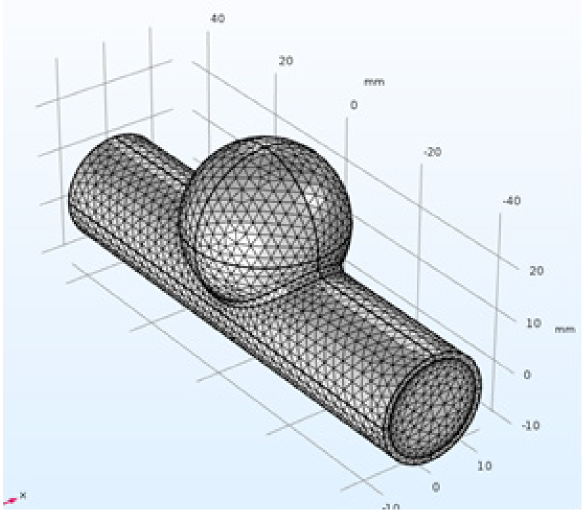

Fig. 5. The finite element grid.

Step 6. In order to solve the multiphysical problem of modeling bag-shaped aneurysm, in principle, you can use the following software environments for finite element modeling: COMSOL Multiphysics [3] and ANSYS [2,4].

The COMSOL software system allows you to model physical processes, which can be described as a system of partial differential equations. With it, you can build finite element models, describe physical processes, form partitioning grids, simulate, and also process calculation results.

The ANSYS software package is designed for structural analysis of engineering and biomechanical structures based on the principles of finite element modeling. With the help of ANSYS it is possible to carry out static, frequency, harmonic, transient dynamic, vibrational structural analysis, as well as finite element analysis - from simple linear static to complex nonlinear dynamic (non-stationary).

Theoretically, COMSOL offers a more correct finite-element design scheme and an intuitive logic of model mapping of mulphysical tasks, however, as applied to the tasks of modeling blood vessels with pathological aneurysmal formations, the ANSYS software system turned out to be more effective in organizing the interface circuit jointly and simultaneously using various design modules and implementing the algorithm solutions of the considered problem. Fig. 6 present this pairing scheme.

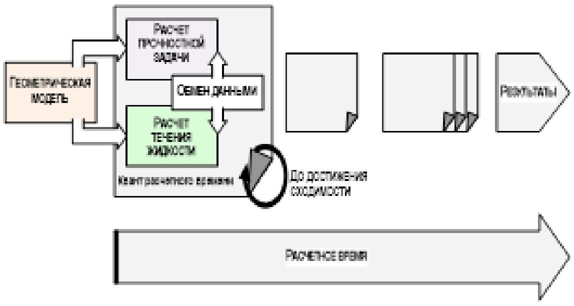

Fig. 6. The scheme of joint solution of multiphysical tasks in ANSYS.

The computational problem in a non-stationary (transient) formulation is based on a single geometric model of the object of research - a vessel (artery) with an aneurysm, including a model of a subregion (domain) in which the blood flow is calculated and the domain of the vessel wall. The computational model process is realized during a given computational (model) time, divided into computational steps (quanta), as a rule, of a fixed size.

Within each quantum, an independent calculation of the strength and hydrodynamic problems takes place. Results are transferred from one domain to another and vice versa. In this case, the force factors of the strength problem affect the shape of the blood flow channel. Theoretically, convergence of the design scheme should be guaranteed by a small time step and automatic restructuring of the computational grid (both of the blood flow channel and the walls). Next, an increment of the estimated time to the specified step occurs, using the results of the previous step as initial ones with the repetition of the process of joint calculation of heterogeneous physical problems.

The described algorithm for solving a model problem with its relatively high labor intensity has certain advantages. In particular, it is very variable and allows the use of various solvers for both the strength problem and the hydrodynamic problem, it is characterized by rather high performance and moderately demanding of computational resources.

The noted qualities made it possible to reproduce the behavior of the blood vessel wall and blood flow under model conditions using the Fluent and Transient Structural modules of the ANSYS package under model conditions, and the Fluent module was used in the double-precision calculation mode. Note also that the need to simulate a nonstationary load in Fluent required the authors to write a small custom UDF procedure.

IV. RESULTS AND DISCUSSION

We now consider some results of numerical finite element modelling. We will conduct computational experiments with an earlier characterized object - a section of a blood vessel (artery) with an aneurysmal formation, the geometric model of which is shown in Fig. 3, and the characteristic dimensions are indicated in section III of this article. Calculations will be carried out at two values of blood pressure: low - 80 mm Hg. and normal - 120 mm Hg. In fig. Figures 7 and 8 present the results of the calculations — diagrams of blood pressure distribution in the vessel and stresses in the vessel wall and aneurysm, respectively, with low (80 mm Hg) and normal (120 mm Hg) blood pressure.

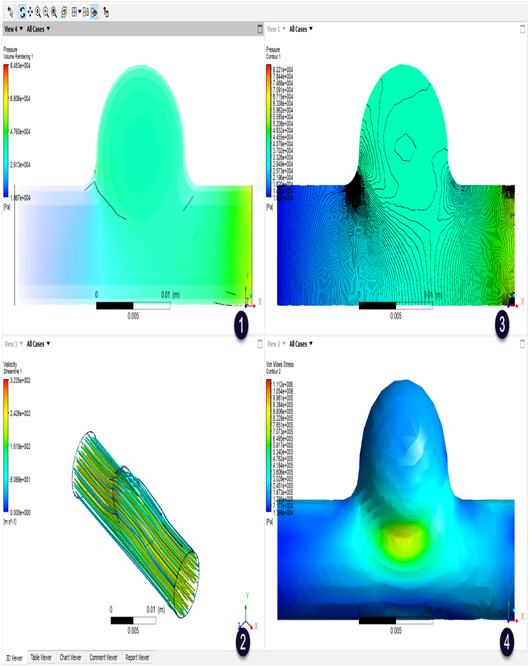

Fig 7. The results of the calculation of blood flow at low pressure (80 mm. Hg). Here: 3 - pressure in the flow in the axial (meridional) section, 4 - stresses in the vessel walls.

In the presented results of model experiments, one can see the blood pressure wave propagating through the vessel (in Fig. 7.1 and Fig. 8.1), and the danger zone exposed to the greatest stresses (in Fig. 7.4 and Fig. 8.4). Also, the analysis of stresses in the vessel walls made it possible to determine the maximum equivalent stresses according to von Mises - see the graph in fig. 9.

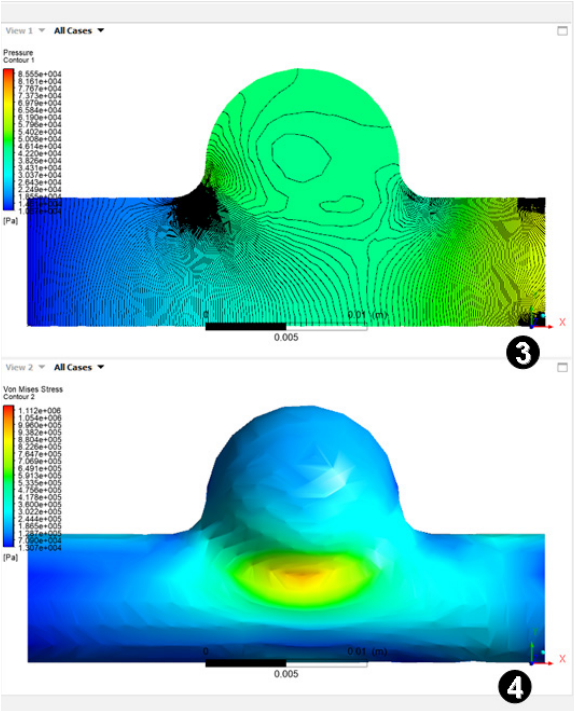

Figure 8. The results of the calculation of blood flow at low pressure (120 mm. Hg). Here: 3 - pressure in the flow in the axial (meridional) section, 4 - stresses in the vessel walls.

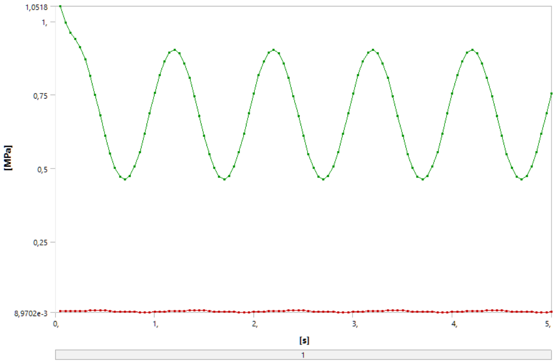

Fig. 9. Graphs of the distribution of blood pressure in the vessel and the maximum equivalent stress according to von Mises in its wall.

From the graph it is seen that the stresses repeat the pressure with some scale factor. This result is not completely physically justified, since it does not demonstrate the expected damped oscillations of the vessel walls and is associated, firstly, with a certain simplification of the artery model with an aneurysm in terms of specifying the vessel fixing mechanisms (fixed support at the ends and missing support on the outer surface) and secondly, using as a source simulating the process of changing blood pressure in a vessel, not a square wave generator, but a sinusoidal load driver.

However, despite the simplifications noted, the finite-element model of an artery with an aneurysm is suitable for computational experiments, since it reflects known patterns and phenomena in vessels affected by aneurysmal formations. At the same time, even the approximate nature of numerical calculations on the model showed that the stresses in the walls at low (Fig. 7.4) and normal (Fig. 8.4) blood pressure differ almost 2 times. From these plots it also follows that the section of the wall of the vessel with the aneurysm, in which the highest stresses are observed, is the zone of transition from the aneurysm to the wall of the bearing blood vessel.

To assess the risk of aneurysm rupture, we plotted surface tangential stress plots at low (Fig. 10) and normal (Fig. 11) pressure of blood in the vessel. In fig. 10 and 11 shows the diagrams of the distribution of tangential stresses in the vessel wall. From the presented plots it is seen that due to the compliance of the wall blood vessel, the danger zone is not on the aneurysm, as such, but on the wall section of the main vessel.

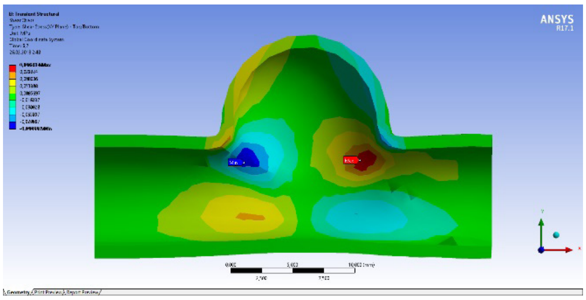

Fig. 10. Distribution of tangential stresses in the vessel wall at low pressure (80 mm Hg).

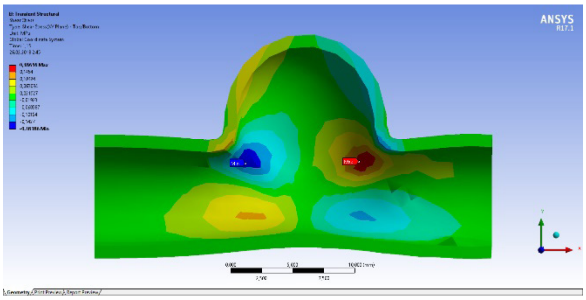

Fig. 11. Distribution of tangential stresses in the vessel wall at normal pressure (120 mm Hg).

V. CONCLUSIONS

The application of the finite element method when conducting numerical modeling of biological objects is a relatively new direction in the theory of elasticity. The problems arising in this problem area are characterized by considerable computational and algorithmic complexity, and verification of the results of computational model experiments does not always give unambiguous results and is not always possible. On the other hand, even the construction of a partially simplified finite-element mathematical model of a biological object often makes it possible to conduct a series of virtual numerical experiments and obtain results on the basis of which certain practical conclusions can be drawn and outlines ways to improve and develop methods of finite element modeling of biological objects. This thesis is well confirmed by the finite element model of the saccular aneurysm of the blood vessel described in this article, as well as by the results of computational model experiments in this model. At the same time, the developed model of the vessel with an aneurysm has demonstrated its suitability and it can be argued that it has practical prospects for use and its further improvement.

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