DEVELOPMENT OF INTERACTIVE TEACHING MATERIALS FOR COMPUTER MECHANICS[1]

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The article discusses the possibilities of using the Wolfram Research technologies, the methodological and technical solutions, which considerably implement a set of tools for creation, maintenance and distribution of the live dynamic content which is recommended for use in the educational process in teaching disciplines and learning sections on the basics of computer modeling in mechanics. The authors explain the typical elements, providing the interactivity of electronic resources, the key constructions, functions and options of the *Mathematica* computer algebra system. The authors give examples from their practice of preparation of teaching materials of the discipline «Computer Modeling» of several specializations.

Key words: interactive educational resources; *Mathematica* computer algebra system; Computable Document Format; computer modeling.

РАЗРАБОТКА ИНТЕРАКТИВНЫХ УЧЕБНЫХ МАТЕРИАЛОВ ПО КОМПЬЮТЕРНОЙ МЕХАНИКЕ

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Обсуждаются возможности применения технологий Wolfram Research, методические и технические решения, которые существенно дополняют набор инструментов создания, сопровождения и распространения живого динамического контента, рекомендуемого к использованию в учебном процессе при преподавании дисциплин и изучении разделов по основам компьютерного моделирования в механике. Поясняются обеспечивающие интерактивность электронных ресурсов типовые элементы, ключевые конструкции, функции и опции системы компьютерной алгебры *Mathematica*. Приведены примеры из практики подготовки учебных материалов дисциплины «Компьютерное моделирование» нескольких специализаций.

Ключевые слова: интерактивные образовательные ресурсы; система компьютерной алгебры *Mathematica*; формат вычисляемых документов; компьютерное моделирование.

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Enhancing the efficiency of the use of information technologies is one of the major trends in the development of the modern educational process [1]. Nowadays hardware and software of computers and the various peripheral devices provide a wide range of possibilities for creating specialized electronic «documents» with intelligence components and dynamic interactivity components. Such materials («documents») have certain advantages over printed materials. An important goal (especially in organizing distance learning) is finding the software which would able to solve the problem of creation and support of the interactive educational resources by a wide community of teachers, including those who don't have any experience in programming.

In this paper we extensively dwell upon the technical solutions described at [2], comprising the use of the technologies developed by Wolfram Research company. In particular, the paper emphasizes the additional features of technical computing system *Mathematica* [3], the Computable Document Format (CDF) [4], the Wolfram Demonstrations Project [5] which allow the users to create, support and freely distribute interactive graphic applications, program units that visually represent the solutions of classic and modern problems of continuum mechanics.

The paper provides examples from the practice of preparing the educational materials for the academic subjects in «Computer Service of Computational Experiment» [6], «Computer Modeling» fields [7]. The specificity of teaching the above-mentioned academic subjects is that many topics of these academic subjects feature theoretical fundamentals of advanced mathematics, the understanding of which requires the use of supporting graphic material, with illustrations of the dynamics of the processes. In particular, it's worth mentioning that the visual representation of the material, the possibility of building imaginary models based on their mathematical descriptions is one of the essential requirements for correctly understanding the meaning of the models and their description. In certain topics of the mentioned subjects not only mathematical component is immensely complicated, but the visual representation is labor intensive as well, that's why it's vital to have the opportunity of their simplification and transformation on a personal computer, in mathematical notation. The general issues of preparing and adapting the relevant interactive freely distributed programmed modules for specific user groups are considered at [8], particularly, the practicality of adopting the *Mathematica* system as the basic platform is proved.

Examples and illustrations of interactive study materials

It is worth noting that the mathematical apparatus of continuum mechanics is represented in *Mathematica* system in a volume exceeding any university textbook. The system includes all known analytic methods for solution of ordinary differential equations and partial differential equations, the solutions are illustrated by examples which the users can change, include in their own applications; mathematical notation grad (gradient), div (divergence), curl, Laplacian is available; all functions of vector analysis are implemented, moreover, in different systems of coordinates. The substantive aspects of computer models studied by undergraduates in specialization subjects taught by the authors of the work are described, in particular, in [2, 3]. A number of representative examples of interactive applications from collections [5] that are used in the studying process, granted to students, and adapted to the topics under study are given below. Methods of setting and adaptation of interactive program organization units are described in [2, 8, 9].

The first series is represented by designs used during the study of the topic «Calculation of the Stress-Strain State of Structures and Their Elements». The basic bridge structures are also exemplified in the selected program organization units. Note that the quest in the search field of the website [5] by the key word «bridge» gives a list of 37 different designs. It includes references to programs with presentations and descriptions of:

• specific bridge structures and models; namely, the following designs: «Cantilever Bridge», «Bridges with Catenary Shaped Supports», «Rolling Bridge», «Dutch Drawbridge», «Bascule (Seesaw) Bridge», «Gateshead Millennium Bridge»;

• generic issues of calculation methods, in particular, the following designs: «Girder Bridge Model», «Analysis of Forces on a Truss», «Bridge Varieties», «Stress Propagation in a Truss Bridge», «Stress-Strain Analysis by the Finite Element Method».

Since the collections [5] contain the source codes, students are provided with program modules, which are included in study materials, not in their original version, but revised. In particular, alternative geometric primitives are suggested for the bearing elements of structures; textual explanations are given with the use of Russian terms; the graphics design is the same as in the basic manuals and textbooks; comments in the modules are translated into Russian, and their volume is significantly increased.

Fragments of module screen copies of this series are given in fig. 1–4, which show screenshots of the control panel and shots with outputs of several program modules.

Change of the parameter values on the panels leads to change in the structure appearance; each control action can be carried out, which is illustrated by fig. 1, by entering the parameter value in the input field or

by moving the slider; it is also possible to play video with automatic parameter changing, to regulate the speed and direction of playing. In all visualization modules in NB-format notebooks and in CDF-documents, the user can not only move sliders on the panels to change geometric parameters, colors, and transparency, but also change the scale of the output 3D-graphics objects and rotate them in different directions.

Figure 1, *a*, shows fragments of the application windows which exemplify some of the all bridge models. There are several views of model of rolling bridge. The rolling bridge is a type of curling movable bridge. A bridge in this model consists of eight triangular sections. Figure 1, *b*, has a platform and a trapezium railing. The top of the adjacent railings are connected with two arms that are hinged to an extendable vertical bar. When the bars are extended the bridge curls up into an octahedral shape.
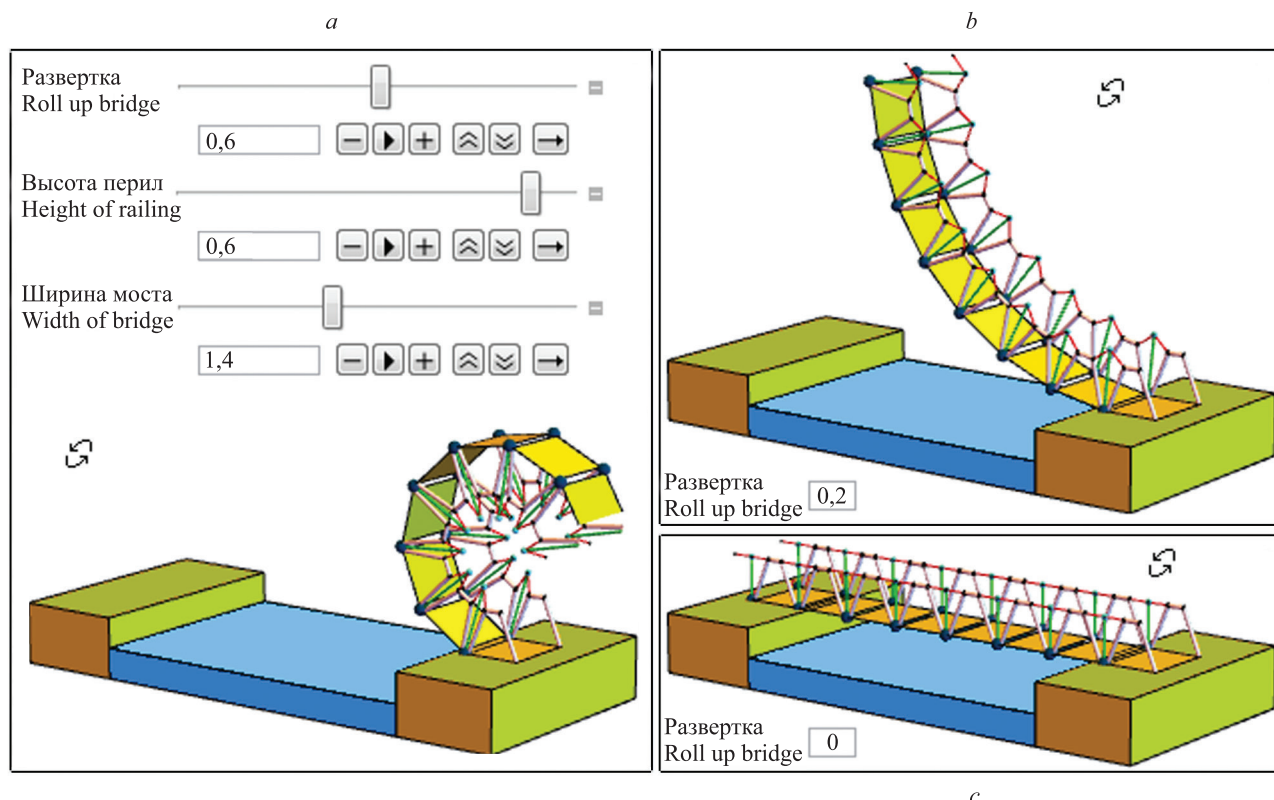

Fig. 1. Illustrations of a control panel of the program unit (*a*) and a rolling bridge model, when roll up bridge: 0,6 (*a*), 0,2 (*b*), 0 (*c*)

Figure 2, *a*, shows the model of Gateshead Millennium Bridge. The bridge is essentially two graceful curves, one forming the deck and the other supporting it, spanning between the two islands running parallel to the quaysides. An inclined catenary supports a horizontal bridge deck with ropes. To allow ships to pass underneath, this whole assembly rotates as a single, rigid structure. Figure 2, *b*, shows the model of cantilever bridge. The overall structure of a cantilever bridge is depicted with the help of cylinders for braces and piers and a cuboid for the deck. User can vary the frequency of units, the arch, the length and width of the bridge, and the diameter of the braces.
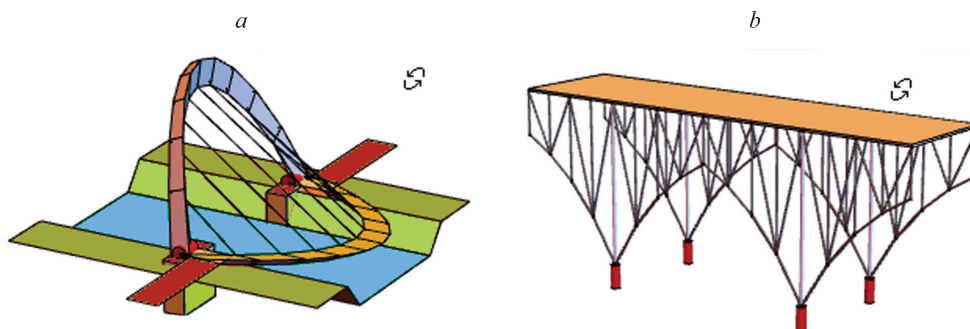

Fig. 2. Screenshots of models of Gateshead Millennium (*a*) and cantilever (*b*) bridges

Figure 3 shows the model of bridges with catenary shaped supports. User can vary values of catenary support, height of deck, pier spacing, diameter of support, support density. When the catenary is convex, we get an arch bridge configuration, with compression stress in the supports. When the catenary is concave, we can see a suspension bridge, with tensile stress in the supports, which would generally be made of stranded steel cables.
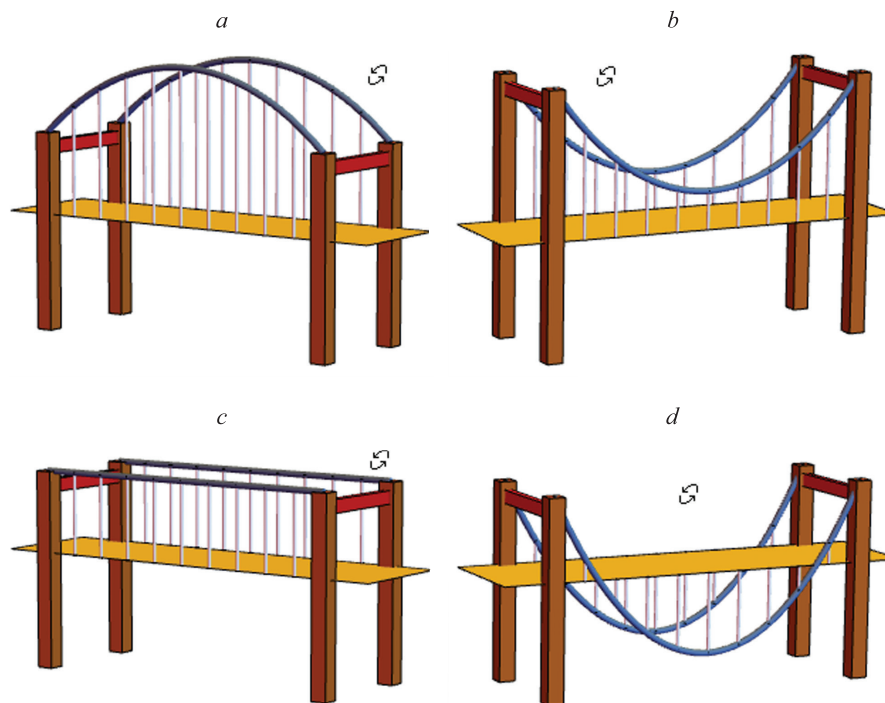

Fig. 3. Screenshots of models of bridges with catenary shaped supports.
Values of catenary support and height of deck: −0,8; 0,2 (*a*); 1,0; 0,5 (*b*); 0; 0,2 (*c*); 1,7; 0,2 (*d*)

Two models of leaf bridges are shown in fig. 4. The deck (leaf) of a bascule (seesaw) bridge is balanced around a fulcrum placed on a pier with the help of a counterweight. The bascule bridge shown in the figure has two leaves, and illustrates a gear drive that uses a pinion attached to the stationary part of the bridge and a gear segment fixed to the leaf.

Booms of presented drawbridge are placed on top of vertical poles. When the booms rotate around axes at the tops of the poles they lift the rectangles at the bases of the poles.
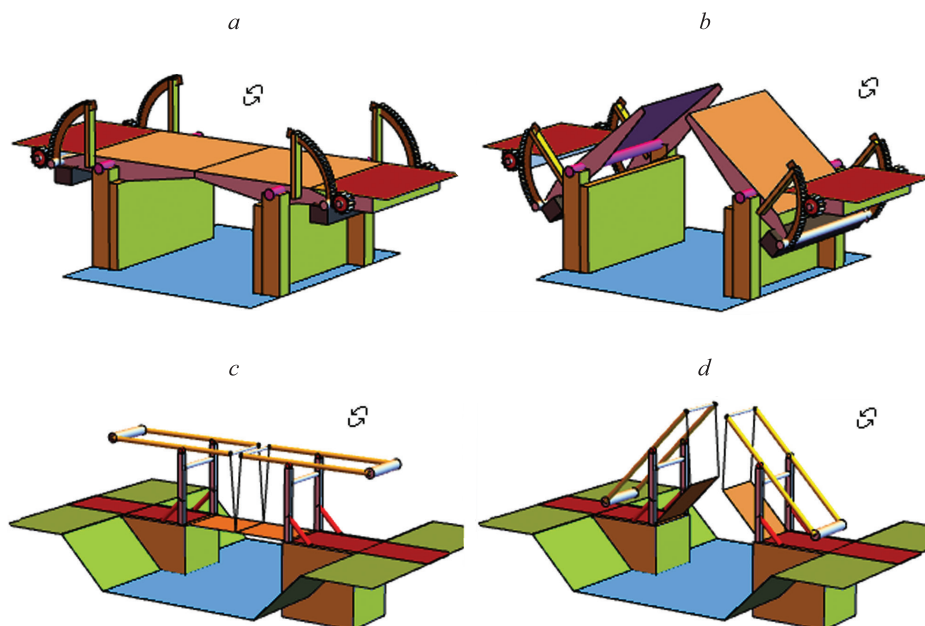

Fig. 4. Screenshots of models of leaf bridges: Bascule (Seesaw) bridge (*a*, *b*), Dutch Drawbridge (*c*, *d*)

Figure 5 shows fragments of the windows of the adapted application «Girder Bridge Model». A girder is supported by two horizontal cylinders. The green cylinder represents a load on the deck between the two supports. The bending moment acting on the given cross-section of the girder is represented by the height of the triangle, the tip of which runs along a parabola while the load is shifted. A dashed red line represents the allowable moment, which is proportional to the thickness of the girder, which in turn is proportional to the strength. User can change the deck thickness, the mass of the loading cylinder or shift it on the deck.
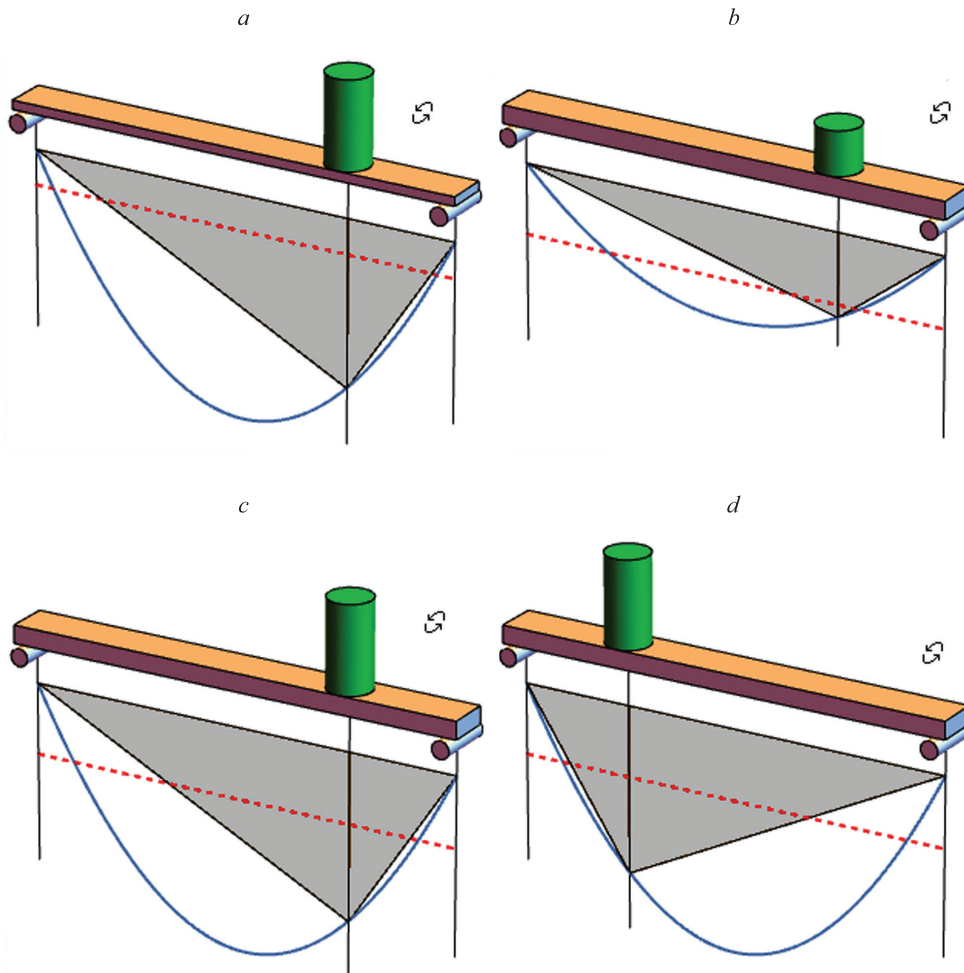

Fig. 5. Examples of visualization of girder bridge model.
Values of load mass, deck thickness, shift the load:
2,0; 0,2; 2,5 (*a*); 1,0; 0,4; 2,5 (*b*); 2,0; 0,4; 2,5 (*c*); 2,0; 0,4; –2,5 (*d*)

Figure 6 shows fragments of the windows of the adapted application «Stress-Strain Analysis by the Finite Element Method», which illustrate visualization models and variants for the results of stress-strain analysis in materials of different structures and in their parts. Rectangles or triangles can be used in the finite element method for the segmentation of the object. Red arrows show the distribution of external forces, while red points show where the object is pinned down. There are several variants of stress analysis, using this program unit. Students can change the input data for geometrical description of the structure, the properties of the materials used in its parts.

The second series is represented by the designs used for studying the topic «Basic Hydrodynamic Models». It is worth mentioning that there are over 120 models of this type in the collection [5]. Students are encouraged to master the models below and program them with certain modifications during practical classes. Illustrations of typical applications of this series are given in fig. 7–9. The basic models of this series used for controlled independent work of students: «Flow through an Open Channel», «Flow of Liquid through a Hole», «Fluid Flow around a Corner», «Couette Flow and Double-Sided Couette Flow», «Laminar Flow between Two Eccentric Tubes», «Streamlines for Laminar Flow Past a Rotating Solid Cylinder», «Velocity Profile for Immiscible Viscous Fluids», «Potential Flow over an Airfoil Specified by Numerical Data File», «Launching a Rocket», «De Laval Nozzle».
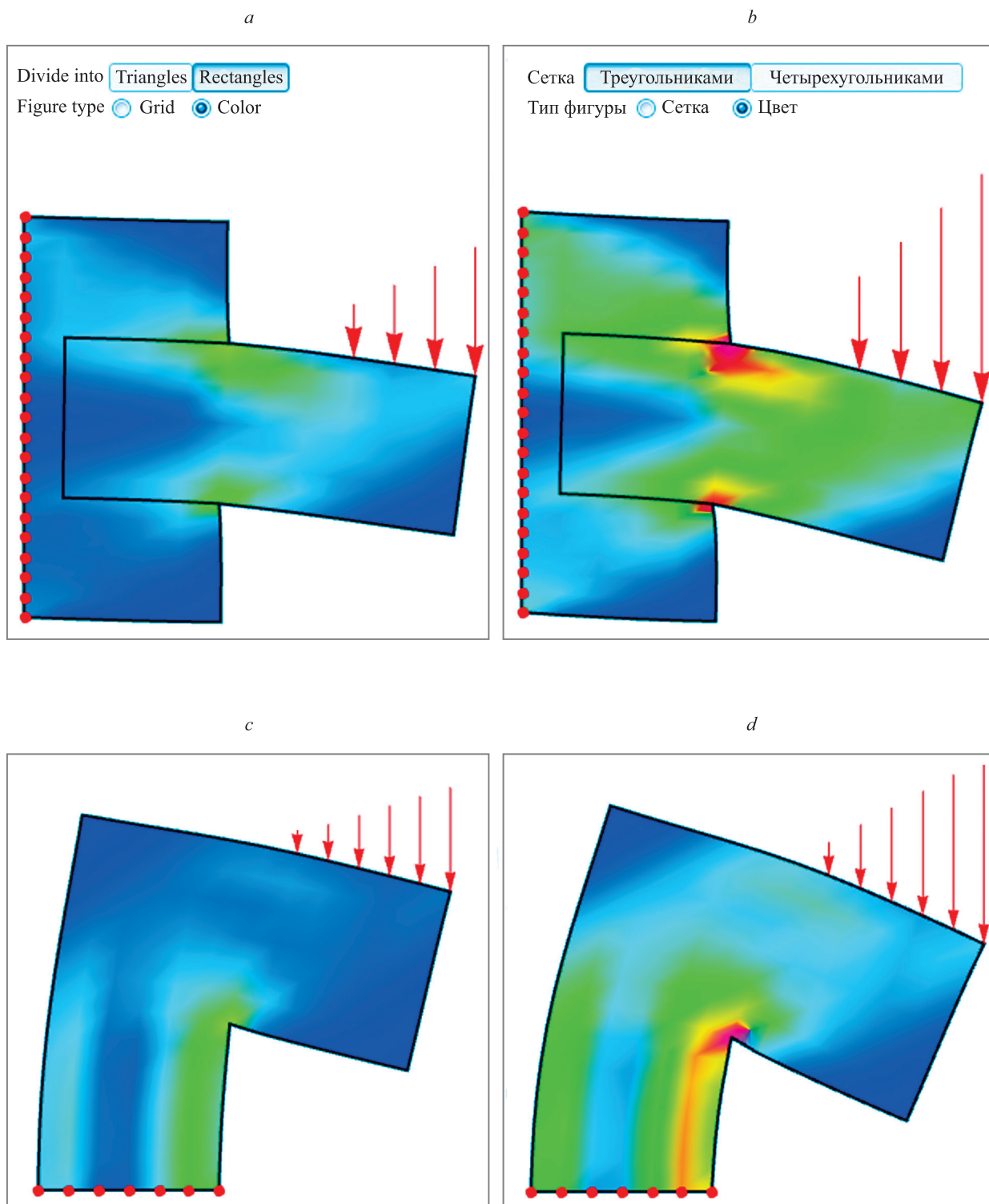
a

b

c

d

Fig. 6. Examples of visualization of stress-strain analysis in different structures.
Values of external force: 0,5 (*a, c*); 0,9 (*b, d*)

Figure 7 shows fragments of the windows of the adapted application «Laminar Flow between Two Eccentric Tubes», isolines of the dimensionless velocity module of a fully developed laminar flow between two eccentric tubes are shown. The dimensionless radius of the outer tube is 1. Using the sliders, user can specify the inner tube radius, eccentricity, the number of collocation points on the other radius, and the number of terms in the series solution.
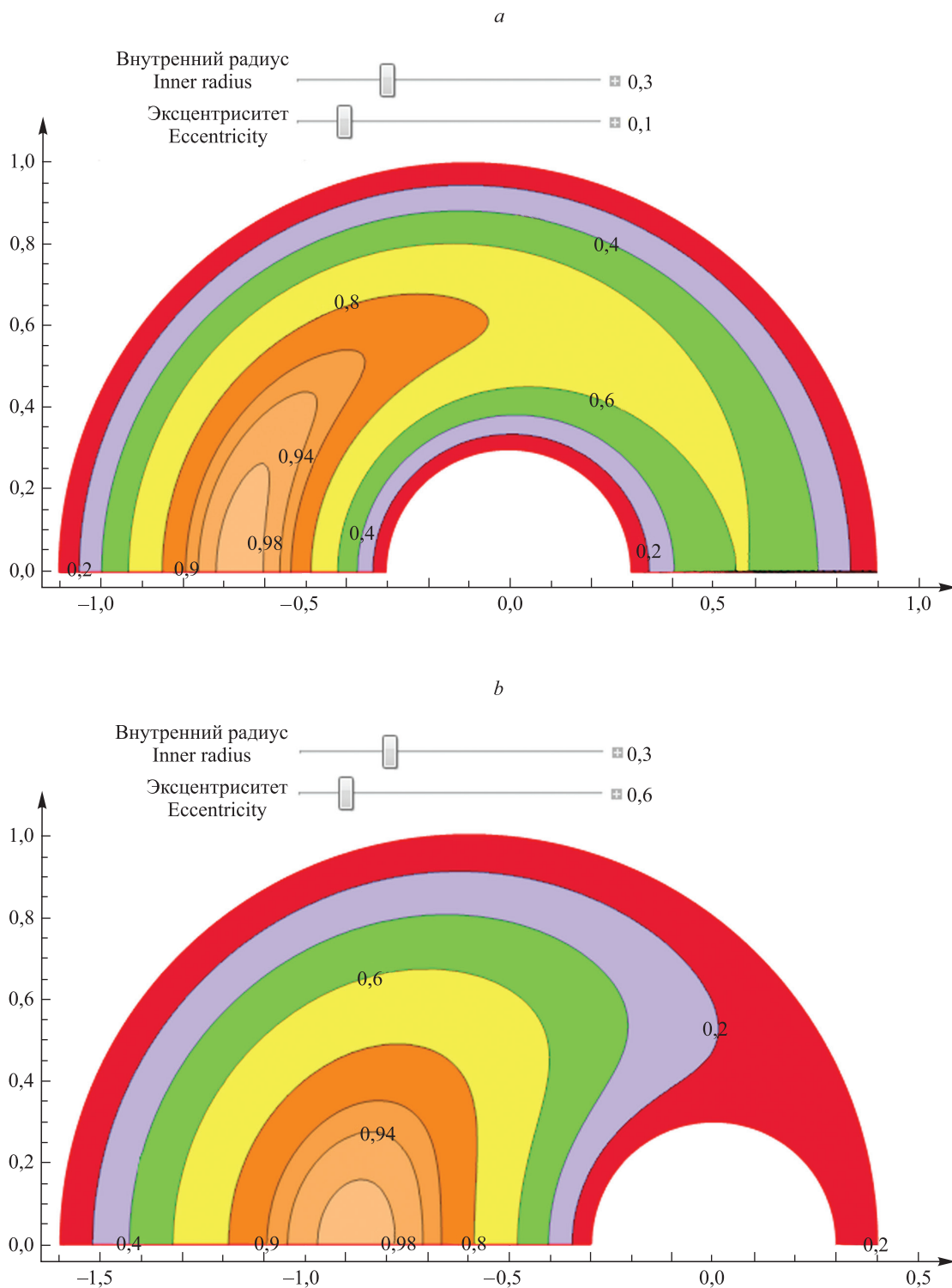
a

Внутренний радиус
Inner radius ☐ 0,3

Эксцентриситет
Eccentricity ☐ 0,1

b

Внутренний радиус
Inner radius ☐ 0,3

Эксцентриситет
Eccentricity ☐ 0,6

Fig. 7. Program unit «Laminar Flow between Two Eccentric Tubes».
The effect of changing the value of eccentricity: 0,1 (*a*); 0,6 (*b*)

Figure 8 shows windows of the adapted application «Velocity Profile for Immiscible Viscous Fluids», which illustrate the behavior of three immiscible fluids subjected to Couette flow. The top plate is moving to the right while the bottom plate is stationary. The velocity of each fluid is given relative to the top plate velocity. The flow is steady, incompressible, and laminar. User can vary each fluid's relative viscosity and height. The velocity distribution indicates the impact of fluid viscosity on each fluid's velocity gradient.
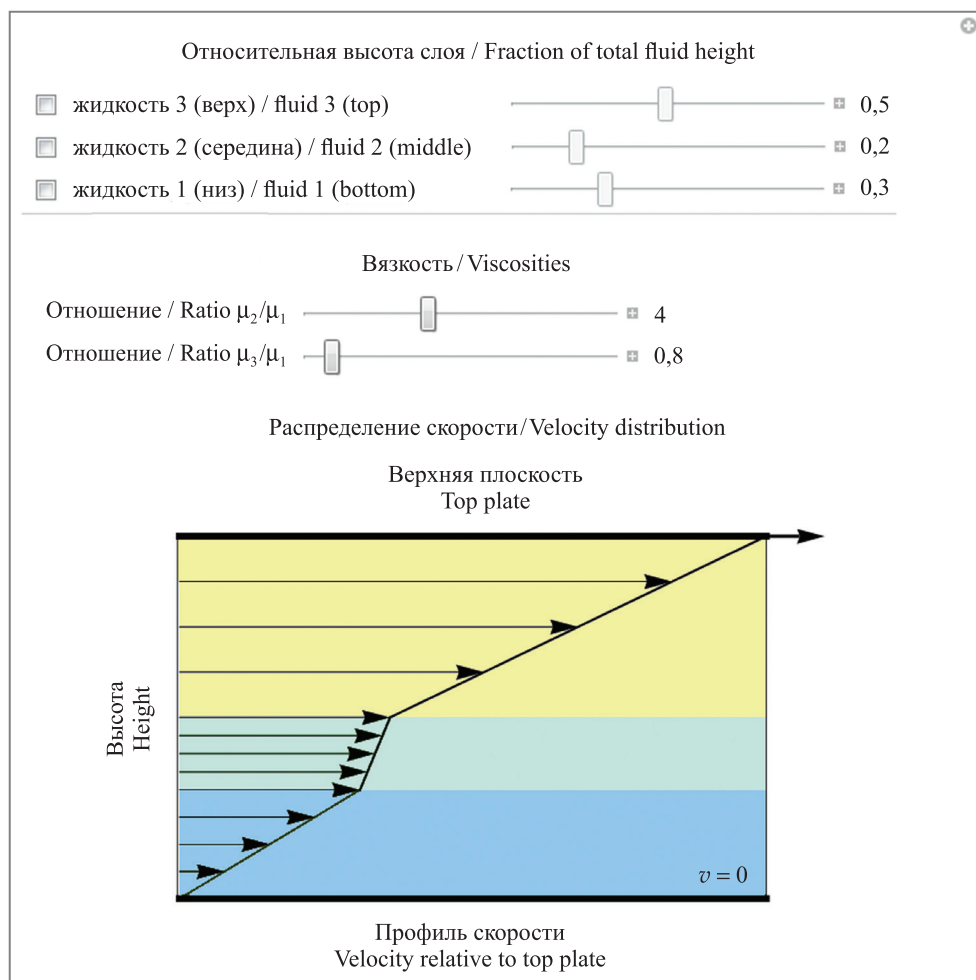
Относительная высота слоя / Fraction of total fluid height

☐ жидкость 3 (верх) / fluid 3 (top)   0,5

☐ жидкость 2 (середина) / fluid 2 (middle)   0,2

☐ жидкость 1 (низ) / fluid 1 (bottom)   0,3

Вязкость / Viscosities

Отношение / Ratio μ_2/μ_1 4

Отношение / Ratio μ_3/μ_1 0,8

Распределение скорости / Velocity distribution

Верхняя плоскость
Top plate

Высота
Height

$v = 0$

Профиль скорости
Velocity relative to top plate

Fig. 8. Example of module with visualization of velocity profile for immiscible viscous fluids

Application «Streamlines for Laminar Flow Past a Rotating Solid Cylinder» is illustrated in fig. 9. Picture shows streamlines of the flow of a uniform, incompressible liquid past a rotating solid cylinder. Streamlines are imaginary lines drawn to illustrate the motion of the liquid; they can be interpreted as trajectories of small, light particles moving with the flow. Depending on the rotation speed, there are one or two stagnation points, displayed as red dots, where the liquid has zero flow velocity. An arrow indicates the magnitude and direction of the cylinder's rotation.
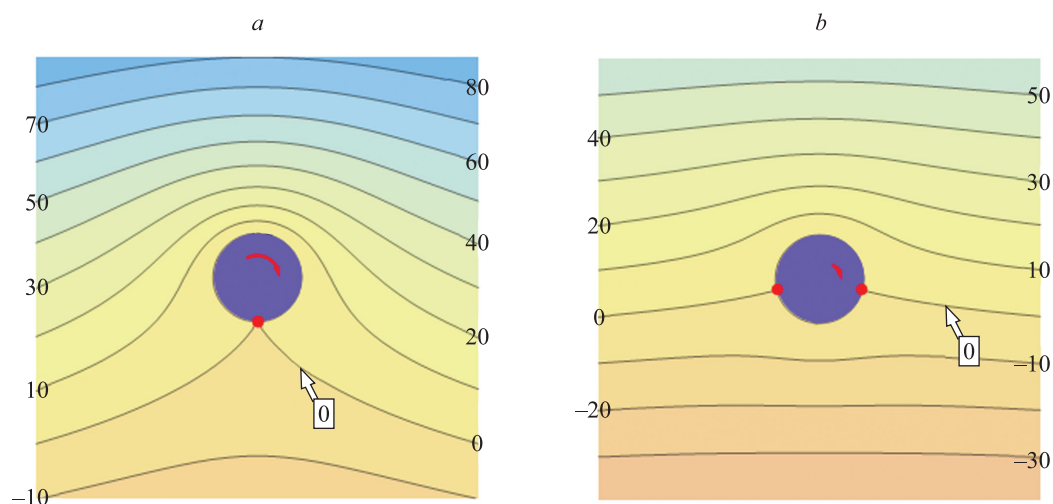
Fig. 9. Example of module with visualization of streamlines.
Values of rotation speed: $40\,\pi$ (*a*); $10\,\pi$ (*b*)

Basic Software Tools

On dynamic interactivity configuration tools. In most cases, dynamic interactivity, dialog boxes, input data parameter management for calculations, construction and viewing of charts are realized in *Mathematica* notebooks with the use of the functions Manipulate, Animate, Dynamic. In particular, Manipulate module helps create various interactive tools according to the set expression 'expr' with arguments (parameters), while the expression 'expr' is treated in its most general form and can be represented by a list with names, mathematical expressions, function graphs, etc. As for explanations in the applications presented to the students, special attention is paid to the issues of dynamic output programming, interactive tool use – examples are given for the functions and options of dynamic calculations, activation and deactivation of indicators, organization of checkboxes, buttons, hierarchical and pop-up menu, locators. Explanations are provided for the following elements: PopupMenu (represents a popup menu with setting and possible values), ActionMenu (represents an action menu with label name), ButtonBar (represents a bar of buttons with labels), Delimiter, CheckboxBar (represents a checkbox bar with setting), RadioButtonBar (a radio button bar with setting), SetterBar (a setter bar with setting), TogglerBar (toggler bar with setting), ControlType (an option for Manipulate and related functions that specifies what type of controls should be displayed), Locator (locator object in the specified position), Slider (represents a slider with setting, the setting can be the dynamically updated), Slider2D (two-dimensional slider), ColorSlider (represents a color slider currently set to the defined color), ListPicker (list picker), AutorunSequencing (an option for Manipulate that specifies how autorun should use the controls provided).

Dynamic interactivity options in CDF-documents. When preparing notebooks in *Mathematica* and planning to save or view them in CDF Player, one should perform initialization (Initialization:->) or save animation parameters (Save Definitions). This is obligatory since CDF Player cannot load user data while in operation. It is allowed to work only with those lists, bundles, and sets that are included in the data base that is all information used by Manipulate function should be embedded in the interactive elements of a CDF-file.

Design. As for the design and scene object view customizing, the exercises include explanations of the rules for setting the line thickness and type (Thickness, Thick, Thin, AbsoluteThickness, Dashed, Dotted, Dot-Dashed), colors and opacity (Colors, Opacity). There are also detailed examples of using the functions and output frame control options: PlotRegion (option for graphics functions that specifies what region of the final display area a plot should fill), PlotRange (option for graphics functions that specifies what range of coordinates to include in a plot), PlotRangeClipping (criteria for clipping the graphics objects at the edge of the region), AspectRatio (the ratio of height to width for a plot), BoxRatios (ratios of side lengths for the bounding box of the three-dimensional picture), Translate (represents graphics primitives translated by the defined vector), Rotate (rotates graphics primitives), GeometricTransformation (represents the result of applying the defined transformation function to the geometric objects corresponding to the primitives), ViewPoint (an option for Graphics3D which gives the point in space from which three-dimensional objects are to be viewed), ViewAngle (an option for Graphics3D which gives the opening angle for a simulated camera used to view the three-dimensional scene).

On the main service functions of computer models. The following functions of *Mathematica* system can be used for model visualization in the presence of analytic description:

- Plot – a plot of an analytic function (or several functions), both scales are linear; the user is able to adjust a number of settings displayed graphs, in particular: ratio of height to width, how to determine the coloring of curves, graphics directives to specify the style for each curve, filling to insert under each curve, style to use for filling, how many mesh points to draw on each curve, the style for mesh points, legends for curves;

- ParametricPlot – generates a parametric plot of a curve or several parametric curves with x and y coordinates, also plots a parametric region or several parametric regions (as well as surface);

- PolarPlot – a plot of a function expressed in polar coordinates, with the radius-vector as a function of the angle in the prescribed range (polar plot);

- Graphics – generation of 2D-graphics primitives (rays, polygons, various triangles, rectangles, parallelograms, rhombs, circles, arcs, segments, B-spline curves, Bézier curves);

- ContourPlot – a contour plot; a plot which shows lines of different levels (isolines); contour plots (or horizontal plots) are used to depict isolines of a scalar data set which are distributed over the surface;

- DensityPlot – a 2-dimensional plot (area map) of a function of two variables where color is used to provide information on the value of the function with respect to the two variables;

- Plot3D – a three-dimensional visualization of an analytic function of two variables prescribed in Cartesian coordinates; the user can work with the plot interactively; scale conversion, rotations, and translations are available;

- ContourPlot3D – a contour plot of a function prescribed in Cartesian coordinates in space; a three-dimensional contour plot also includes isolines showing the edges of 3D-shape layers in the cutting planes located in parallel to the supporting plane of the figure;
- RegionPlot3D – geometric figure visualization in space;
- DensityPlot3D – a space plot illustrating spatial distribution of the prescribed function of two variables on the basis of a continuous color scheme or specially set color scheme;
- ParametricPlot3D – a plot of a parametric curve or surface in space;
- SphericalPlot3D – a plot in spherical coordinates, generates a 3D-plot with a spherical radius r as a function of spherical coordinates θ and φ.

In cases when mathematical description of models is created on the basis of approximation in accordance with the results of observations and measurements on regular or irregular grids (on a scattered point set), the following functions can be used:

- ListPlot – a scatter plot; shows a plot of the list of values the coordinates of which are set by the list values;
- ListLinePlot – a line plot by data list points (list of values or list of coordinate-value pairs);
- ListStepPlot – a step plot according to the value list;
- ListPolarPlot – a scatter plot in polar coordinates;
- DateListPlot – a calendar time plot;
- TimeSeries – a time series (represents a time series specified by time-value pairs);
- ListContourPlot – a contour plot according to the value array, the method of interpolation and data reduction can be set;
- ListDensityPlot – a density plot according to the value array;
- ListPlot3D – a three-dimensional scatter plot, spatial representation of a surface according to an array of height values in points;
- ListContourPlot3D – a 3D-contour plot according to the value array;
- ListSurfacePlot3D – a 3D-plot of a surface reproduced according to the point list;
- ListPointPlot3D – a 3D-scatter plot, spatial generation of images of points with three set coordinates;
- ListDensityPlot3D – a space density plot according to data.

Tools and functions for work with vector fields:

- StreamPlot – a stream plot (flow diagram), generates a stream plot of the vector field ore several vector fields;
- StreamDensityPlot – a stream plot superimposed on a background density plot (density flow diagram);
- VectorPlot – a vector plot (vector diagram), generates a vector plot of the vector field;
- VectorDensityPlot – a vector density diagram;
- ListVectorPlot – a vector diagram formed based on data, the method of interpolation and data reduction can be set;
- ListVectorDensityPlot – a density vector diagram based on data;
- ListStreamPlot – a flow rate diagram formed according to data charts, that is approximation is followed by flow line plotting;
- ListStreamDensityPlot – a density diagram of flow rate according to data;
- ArrayPlot – an array image; generation of an image where array values correspond to colored squares;
- VectorPlot3D – a spatial vector diagram (vector fields);
- ListVectorPlot3D – a 3D-vector diagram according to data.

Conclusion

The work gives typical examples of use in the process of teaching subjects on the computer modeling fundamentals in the mechanics of live dynamic content created and supported on the basis of the proposed method of *Mathematica* tool integration, CDF-format, modules of freeware interactive application collection. The work also defines and specifies basic software tools recommended for the method implementation.

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