N E W S
OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC OF KAZAKHSTAN
SERIES OF GEOLOGY AND TECHNICAL SCIENCES
ISSN 2224-5278 **https://doi.org/10.32014/2018.2518-170X.38**
Volume 5, Number 431 (2018), 85 – 94

ISRSTI 30.15.15
UDC 531.011

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CALCULATION AND VISUALIZATION OF A BODY MOTION UNDER THE GRAVITY FORCE AND THE OPPOSING DRAG

Abstract. The article presents the calculations and visualization of a body motion in a gravitational field with opposing drag force made by using MatLab program. There is the description of the physical phenomenon and its mathematical model. The differential equations of a body motion are written for the dimensionless quantities that allow applying them for each body moving in gravitational field. The m-file is developed under the name Gravitation and the file listing is given for solving the system of differential equations in the Matlab system. The solution of differential equations is carried out by using the ode45 procedure. Since the calculation accuracy by default (10^{-6}) has been low it is increased up to 10^{-9}. Results of calculations are presented in the form of graphs of a body motion trajectory and the graphs of x – coordinates versus time , x – components of a body velocity versus time at the drag coefficient of k1=0, k1=0.5, k1=1 and k1=2. It is discovered that at the action of the drag force of the medium the body gradually falls toward the attracting center. The article contains the assignments for student's self-study work. The results of calculations and visualization of a body motion in a gravitational field with opposing drag force are applied in classical mechanics.

Key words: gravitational field, orbit, period, trajectory, drag force.

Introduction. Nowadays all educational institutions of Kazakhstan are provided with computer hardware and software, interactive boards and internet. Almost all teachers have completed language and computer courses for professional development. Hence the educational institutions have all conditions for using computer training programs and models for performing computer laboratory works. During several years we have been conducting the work on organization computer laboratory works on physics with use of resources of the Fizikon Company [1, 2] which are developed at Al-Farabi Kazakh National University by V. V. Kashkarov and his group. Some of worksheet templates for computer laboratory works are introduced in educational process of our university and schools of the Southern Kazakhstan [3-31]. Students of the physics specialties 5B060400 and 5B011000 successfully master the discipline "Computer modeling of physical phenomena" which is the logical continuation of the disciplines "Information technologies in teaching physics" and "Use of electronic textbooks in teaching physics". The aim of this discipline is to study and learn the MATLAB program language [32] system, acquaintance with its huge opportunities for modeling and visualization of physical processes. The present article is devoted to calculation and visualization of a body motion in a gravitational field with opposing drag force by using the package of MATLAB applied programs.

Description of the physical phenomena. Let the material body (the space station) of the mass *m* to move through a certain medium under the action of the attracting motionless center O. For example, a body moves under the action of an attraction force of a celestial body (in particular, the gravitational force of the Earth). Since the medium opposes the motion of the body, its energy decreases and eventually it falls on the attracting center. Hence, the moving body experiences two forces: the gravity force directed towards the attracting center O

$$\vec{F} = -G\frac{Mm}{r^3}\vec{r}$$

and the opposing drag force of the medium

$$\vec{F}_1 = k_1 m\vec{\upsilon}$$

Differential equation of motion can be derived from the Newton's second law:

$$m\frac{d^2\vec{r}}{dt^2} = \vec{F} + \vec{F}_1 \quad (1)$$

By taking the projections on coordinate axes of all forces, acting on the body we get the following system of differential equations:

$$\frac{d\upsilon_x}{dt} = -GM\frac{x}{\left(x^2+y^2\right)^{3/2}} - k_1\upsilon_x; \quad \frac{d\upsilon_y}{dt} = -GM\frac{y}{\left(x^2+y^2\right)^{3/2}} + k_1\upsilon_y \quad (2)$$

$$\frac{dx}{dt} = \upsilon_x; \quad \frac{dy}{dt} = \upsilon_y \quad (2a)$$

The initial conditions are: $x(0) = x0$, $\upsilon_x(0) = 0$, $y(0) = 0$; $\upsilon_y(0) = \upsilon0$, which mean that the material body at the initial moment of time is located on the axis Ox at the point x0 and its corresponding velocity along axis Ox is zero but its initial velocity along axis Oy is equal to $\upsilon0$.

Formulation of the problem. Work out the program for calculation and visualization of the body motion in the gravitational field of a massive object by using the MatLab program.

For solving the system of differential equations (2) it is necessary to make these equations dimensionless. As the measurement unit of the distance and time we take the orbit radius *R* and the revolution period *T*, corresponding to the motion of the body along the circle and introduce the variables X = x/R, Y = y/R, $\tau = \frac{t}{T}$, where $T = \sqrt{\frac{4\pi^2 R^3}{GM}}$. In the first two terms of the equation (2) the substitution of the variables x, y, t by the variables X,Y,τ gives

$$\frac{d^2X}{d\tau^2} = -\frac{4\pi^2}{\left(X^2+Y^2\right)^{3/2}}X, \quad \frac{d^2Y}{d\tau^2} = -\frac{4\pi^2}{\left(X^2+Y^2\right)^{3/2}}Y \quad (3)$$

The equations (3) are universal since they depend neither upon the revolution period around the field center nor upon the orbit radius. Therefore, the quantity T^2/R^3 is identical for all bodies moving in a gravitational field along the closed path. The given relationship is the proof of validity of Kepler's third law.

For working out the program for the given problem by using the MatLab system the following denotations are introduced into the equations (2) and (3):

$$X = z_1, \quad \frac{dX}{dt} = z_2, \quad Y = z_3, \quad \frac{dY}{dt} = z_4$$

$$\frac{dz_1}{d\tau} = z_2; \quad \frac{dz_3}{d\tau} = z_4; \quad \frac{dz_2}{d\tau} = -\frac{4\pi^2 z_1}{\left(z_1^2+z_3^2\right)^{3/2}} - k_1 z_2; \quad \frac{dz_4}{d\tau} = -\frac{4\pi^2 z_3}{\left(z_1^2+z_3^2\right)^{3/2}} + k_1 z_4$$

and m-file under the name Gravitation is created.

The m-file listing

```
function dy=Gravitation(t,z)
global k1
dy=zeros(4,1); % input the column-vector with dimension 4x1
dy(1)=z(2);
dy(2)=-4*pi^2*z(1)/((z(1)^2+z(3)^2).^1.5) -k1*z(2);
dy(3)=z(4);
dy(4)=-4*pi^2*z(3)/((z(1)^2+z(3)^2).^1.5)+k1*z(3);
end
```

At first let the medium drag to be zero (k1=0) and the initial conditions to be x(0) = 0, y(0) = 0, υx0 = 0, υy0 = 2, i.e. the body doesn't have the velocity component along the Ox-axis but it has the velocity component along the Oy-axis. (υx0 = υ0·cos(a), υy0 = υ0·sin(a), υ0 = 2).

The trajectory of the body motion through medium without drag force. In the command line we write

```
>> global k1
>> k1=0;
>> v0=2;
>> x0=1;y0=0;
>> a=pi/6;
>> vy0=2;
>> vx0=0;
>> [t,Y]=ode45('Gravitation',[0:10^-5:2.5],[x0 vx0 y0 vy0]);
>> subplot(2,2,1); plot(Y(:,1),Y(:,3));
>> grid on
>> tol=1e-9;
>> [t,Y]=ode45('Gravitation',[0:10^-5:2.5],[x0 vx0 y0 vy0],odeset('RelTol',tol));
>> subplot(2,2,2); plot(Y(:,1),Y(:,3));
>> grid on
```

At the given conditions the body moves along the circle (figure 1). The trajectory blurring (fig1A) is explained by the low calculation accuracy. Therefore, the calculation accuracy is increased up to 10^{-9} with the help of the odeset45 procedure. The result is given in the figure 1B.

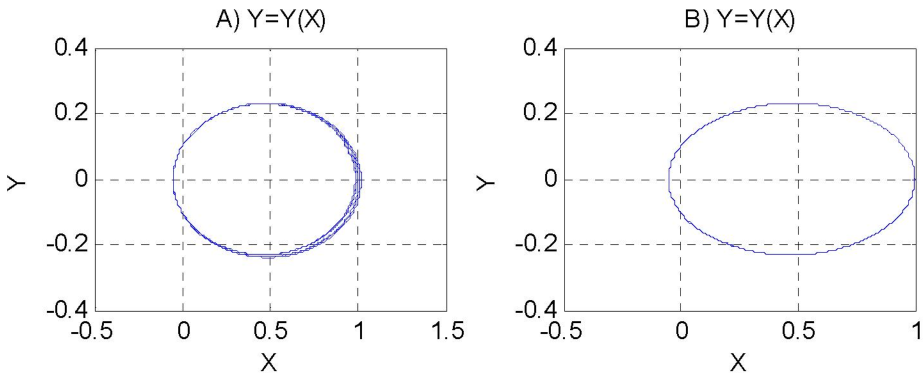

Figure 1 – The trajectory of the body motion through medium without drag force

The motion of the body through the medium under the action of the gravity force and the opposing drag force.

```
>> global k1
>> k1=0.5;
>> tol=1e-9;
>> [t,Y]=ode45('Gravitation',[0:10^-5:2.5],[x0 vx0 y0 vy0],odeset('RelTol',tol));
>> plot(Y(:,1),Y(:,3));
>> grid on
```

The result is presented in the figure 2.

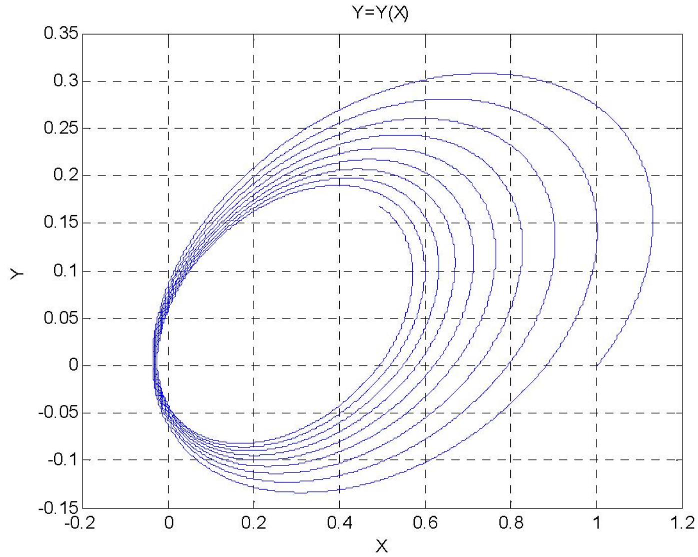

Figure 2 – The trajectory of the body motion at k1=0.5

```
>> plot(t,Y(:,1));
>> grid on
```

The result is presented in the figure 3.

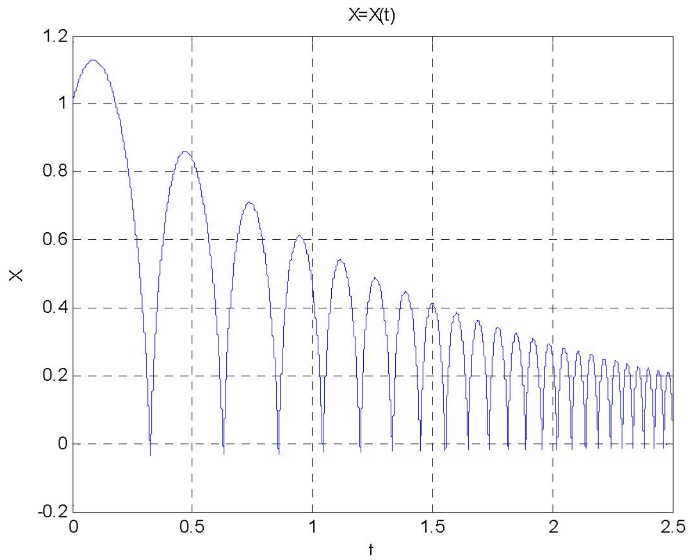

Figure 3 – The graph of the coordinate X versus time at k1 = 0.5

The dependence of x-component of the body velocity upon the time

```
>> plot(Y(:,3));
>> grid on
```

The result is presented in the figure 4.

```
>> k1=1;
>> tol=1e-9;
>> [t,Y]=ode45('Gravitation',[0:10^-5:2.5],[x0 vx0 y0 vy0],odeset('RelTol',tol));
>> plot(Y(:,1),Y(:,3));
>> grid on
```

The result is presented in the figure 5.

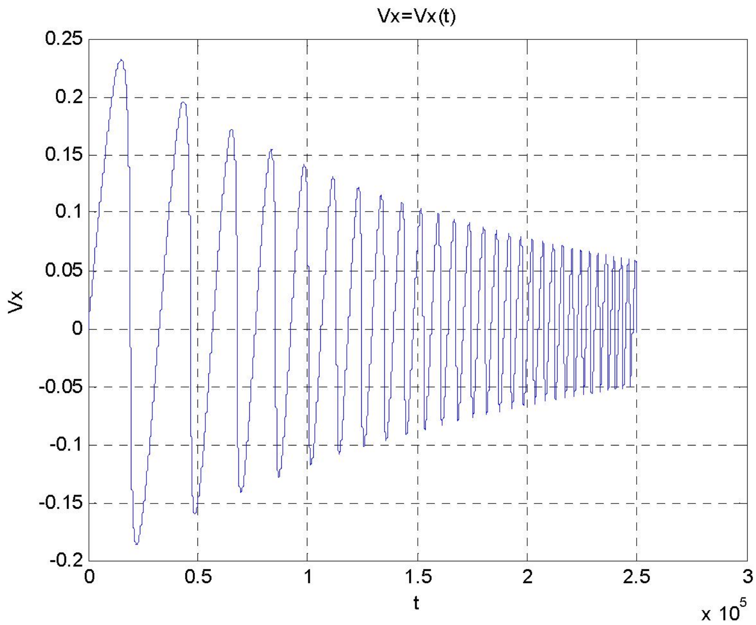

Figure 4 – The graph of x-component of the body velocity versus time at k1 = 0.5

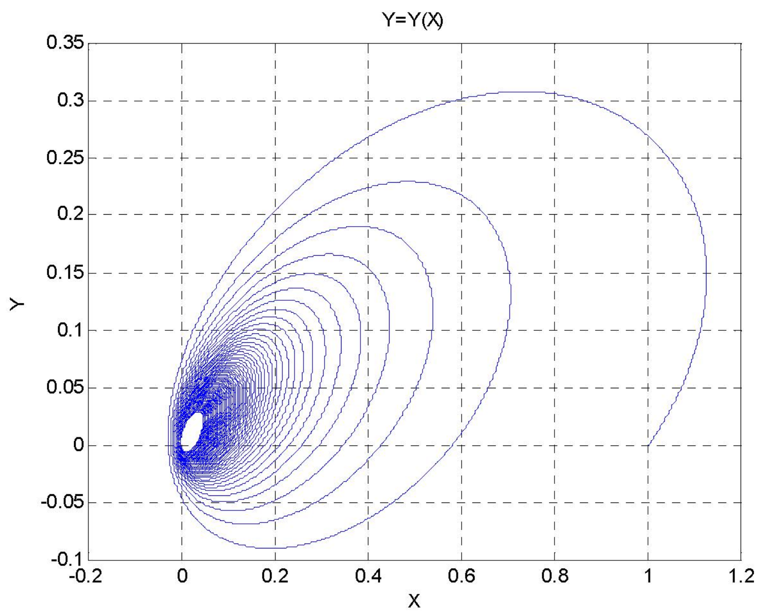

Figure 5 – The trajectory of the body motion at k1=1

```
>> plot(t,Y(:,1));
>> grid on
```
The result is presented in the figure 6.
```
>> plot(Y(:,3));
>> grid on
```
The result is presented in the figure 7.
```
>> k1=2;
>> tol=1e-9;
>> [t,Y]=ode45('Gravitation',[0:10^-5:2.5],[x0 vx0 y0 vy0],odeset('RelTol',tol));
>> plot(Y(:,1),Y(:,3));
>> grid on
```
The result is presented in the figure 8.

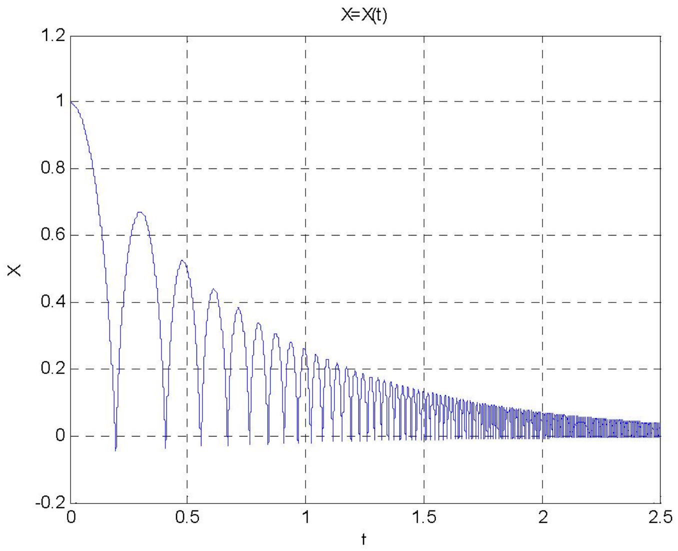

Figure 6 – The graph of the coordinate X versus time at k1 = 1

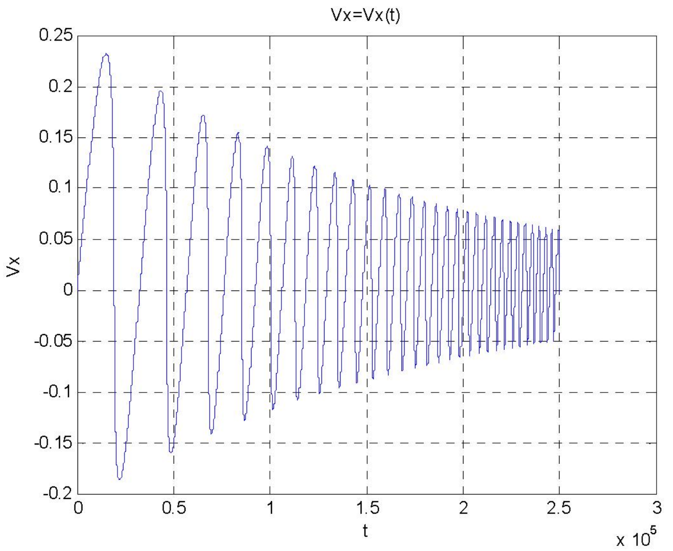

Figure 7 – The graph of x-component of the body velocity versus time at k1 = 1

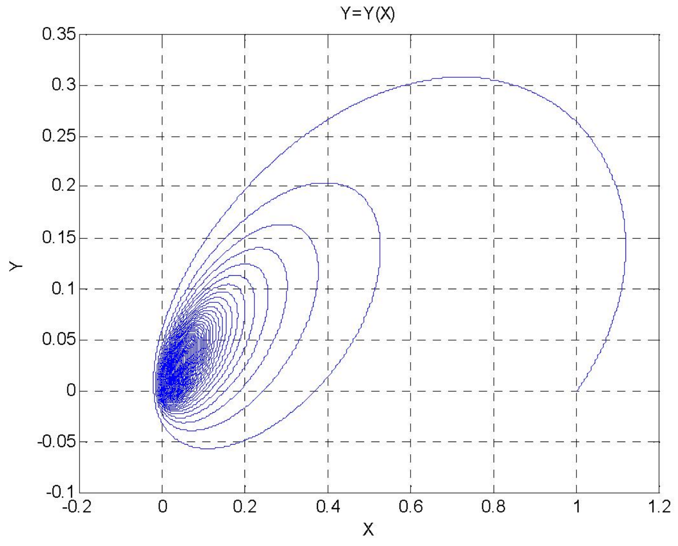

Figure 8 – The trajectory of the body motion at k1=2

```
>> plot(t,Y(:,1));
>> grid on
```

The result is presented in the figure 9.

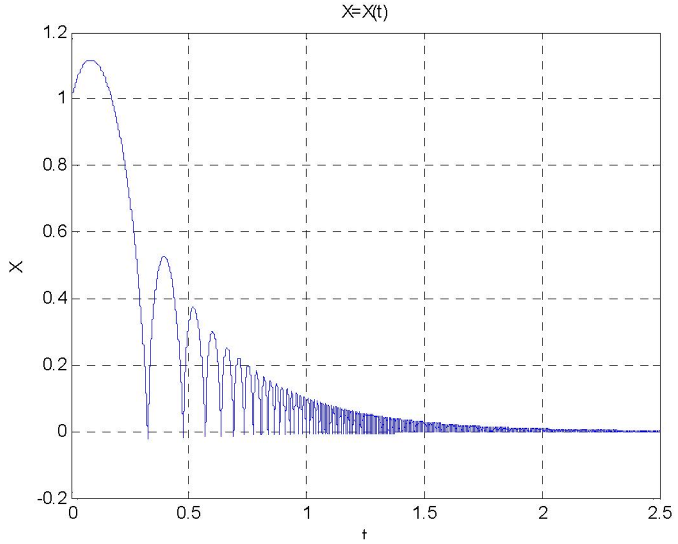

Figure 9 –The graph of the coordinate X versus time at k1 = 2

```
>> plot(Y(:,3));
>> grid on
```

The result is presented in the figure 10.

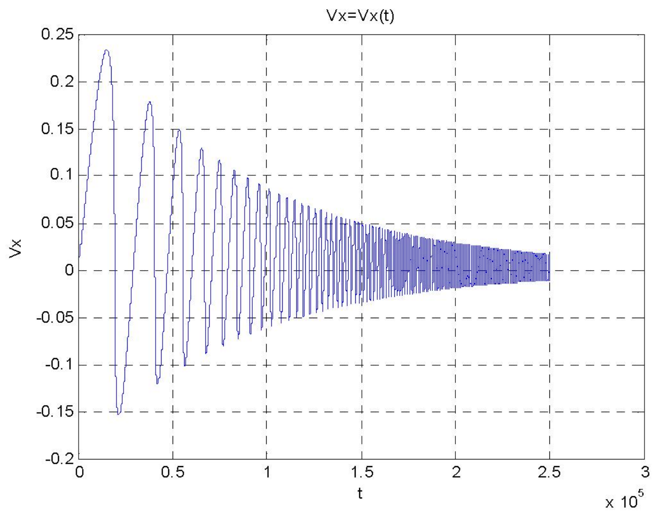

Figure 10 – The graph of x-component of the body velocity versus time at k1 = 2

There are assignments for self-study:

1. For the case of a body motion under the action of two forces, a gravity force and a drag force, make the body to fall on the attracting center by increasing its motion time.

2. Perform the experiment for different values of the medium drag coefficient by changing it from 1.00 up to 2.00 with step 0.10 and find at what value of the drag coefficient the body falls on the attracting center, draw the trajectories of motion, graphs of x-coordinate versus time and of x-component of the body velocity versus time when the initial conditions and time of motion do not change.

Conclusion. The article presents the calculations and visualization of the body motion through medium under the action of the gravitational force and opposing drag force. There is the description of the physical phenomenon and its mathematical model. The differential equations of a body motion are written for the dimensionless quantities that allow applying them for each body moving in gravitational field. The m-file is developed under the name Gravitation and the file listing is given for solving the system of differential equations. The solution of differential equations is carried out by using the ode45 procedure. Since the calculation accuracy by default (10^{-6}) has been low it is increased up to 10^{-9}. Results of calculations are presented in the form of graphs of a body motion trajectory and the graphs of x – coordinates versus time , x - components of a body velocity versus time at the drag coefficient of k1=0, k1=0.5, k1=1 and k1=2. It is discovered that at the action of the drag force of the medium the body gradually falls toward the attracting center. The article contains the assignments for student's self-study work. The results of calculations and visualization of a body motion in a gravitational field with opposing drag force are applied in classical mechanics.

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ДЕНЕНІҢ АУЫРЛЫҚ ЖӘНЕ КЕДЕРГІ КҮШТЕР ӘСЕРІНЕН ҚОЗҒАЛЫСЫН ЕСЕПТЕУ ЖӘНЕ БЕЙНЕЛЕУ

Аннотация. Гравитацияық өрісте қозғалған денеге кедергі күші әсер еткен жағдайды есептеу және бейнелеу ұсынылады. Физикалық құбылыс сипатталып, математикалық модель құрылған. Дене қозғалысының дифференциалдық теңдеулер жүйесі өлшемсіз шамалар арқылы өрнектелген, мұндай өрнектеу кез келген дененің гравитациялық өрістегі қозғалысы үшін қолдануға мүмкіндік береді. Дифференциалдық теңдеулер жүйесін шешу үшін ode45 процедурасы қолданылған, есептеудің дәлдігі (10^{-6}) жетіспегеннен кейін ол дәлдік 10^{-9} етіп өзгертілген. Есептеулер нәтижелері дене қозғалысының траекториясы түрінде бейнеленген және дененің x-координатысының, жылдамдығының x-компонентінің уақытқа тәуелділік графиктері арқылы бейнеленген (k1=0, k1=0.5, k1=1 және k1=2 шамалары үшін). Кедергі күш әсерінің нәтижесінде дене тартылыс центріне құлайтыны көрсетілген. Өз бетінше орындауға арналған тапсырмалар ұсынылған. Есептеу және бейнелеу нәтижелері классикалық механикада қолданылады.

Түйін сөздер: гравитациялық өріс, орбита, период, траектория, кедергі күш.

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РАСЧЕТ И ВИЗУАЛИЗАЦИЯ ДВИЖЕНИЯ ТЕЛА ПОД ДЕЙСТВИЕМ СИЛЫ ТЯГОТЕНИЯ И СИЛЫ СОПРОТИВЛЕНИЯ СРЕДЫ

Аннотация. В статье приведены расчеты и визуализация движения тела в гравитационном поле при наличии силы сопротивления. Дано описание физического явления, создана математическая модель. Дифференциальные уравнения движения тела написаны в безразмерных величинах, что позволяет примененить их для любого тела, движущегося в гравитационном поле. Для решения системы дифференциальных уравнений в системе Matlab созданm-файл под названием Gravitation и дан листинг файла. Решение дифференциальных уравнений осуществлено с помщоью процедуры ode45 и так как точность вычисления по умалчанию (10^{-6}) оказалась недостаточной она повышена до 10^{-9}. Результаты вычислений представлены в виде графиков траектории движения тела и графиков зависимости x-координаты от времени, x-компоненты скорости движения тела от времени при значениях коэффициента сопротивления среды k1=0, k1=0.5, k1=1 и k1=2. Установлено, что при наличии силы сопротивления среды тело постепенно падает на притягивающий центр. Предложены задания для самостоятельной работы. Результаты вычислений и визуализации применяются в классической механике.

Ключевые слова: гравитационное поле, орбита, период, траектория, сила сопротивления.

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