ФЕДЕРАЛЬНОЕ ГОСУДАРСТВЕННОЕ АВТОНОМНОЕ ОБРАЗОВАТЕЛЬНОЕ
УЧЕРЕЖДЕНИЕ ВЫСШЕГО ОБРАЗОВАНИЯ
«Санкт-Петербургский политехнический университет Петра Великого»

Институт компьютерных наук и технологий
Высшая школа программной инженерии

Отчет по курсовой работе по дисциплине «Математические модели»

Выполнила студентка гр. 3530904/80001 Прохорова А. И.

Руководитель Устинов С. М.

Санкт-Петербург
2020

1 Задание

Для **МОДЕЛИ 3** в плоскости параметров **(p4, p6)** построить бифуркационные диаграммы точек поворота (**p4, p6** > 0). При построении диаграммы целесообразно использовать логарифмический масштаб (log(**p4**,**p6**)) по обеим осям. Убедиться, что это точки поворота, а не ветвления. Проиллюстрирова количество решений в каждой области.
(p1 = 8.4e-6, p2 = 6.6667e-4, p3 = 1.7778e-5, p5 = 2).

$\frac{dx_1}{dt} = (p_1x_2 - x_1x_2 + x_1 - x_1^2)/p_2 - p_4x_1;$
$\frac{dx_2}{dt} = (-p_1x_2 - x_1x_2 + p_5x_3)/p_3 + p_4(p_6 - x_2);$
$\frac{dx_1}{dt} = x_1 - x_3 - p_4x_3;$

2 Блок аналитических преобразований

Будем решать систему, в качестве ε варьируя p_4

$$\begin{cases} det(J_N) = 0 \\ f(x, \varepsilon) = 0 \end{cases} \tag{1}$$

Посчитаем матрицу Якоби:

$$J_N = \begin{pmatrix} -\frac{x_2}{p_2} + \frac{1}{p_2} - \frac{2x_1}{p_2} - p_4 & \frac{p_1}{p_2} - \frac{x_1}{p_2} & 0 \\ -\frac{x_2}{p_3} & -\frac{p_1}{p_3} - \frac{x_1}{p_3} - p_4 & \frac{p_5}{p_3} \\ 1 & 0 & -1 - p_4 \end{pmatrix}$$

Запишем систему $f(x, p_4) = 0$:

$$\begin{cases} (p_1x_2 - x_1x_2 + x_1 - x_1^2)/p_2 - p_4x_1 = 0; \\ (-p_1x_2 - x_1x_2 + p_5x_3)/p_3 + p_4(p_6 - x_2) = 0; \\ x_1 - x_3 - p_4x_3 = 0; \end{cases} \tag{2}$$

Из первого уравнения выразим x_2 через x_3, из третьего уравнения выразим x_3 через x_1:

$x_2 = \frac{x_1^2 + p_2p_4x_1 - x_1}{p_1 - x_1}$
$x_3 = \frac{x_1}{1+p_4}$

Подставим их в уравнение $det(J_N) = 0$ и получим кубическое уравнение относительно x_1. Находим корни, подставляем их в выражения для x_2 и x_3.

p_6 можем найти из второго уравнения:

$p_6 = \frac{p_1x_2 + x_1x_2 - p_5x_3}{p_3p_4} + x_2$

3 Блок проверки

Проверку реализуем несколькими способами. При подстановке полученных значений в исходные данные:

1. Равенства в системе должны соблюдаться:
   $f(x, p_4, p_6) = 0$
2. Определитель матрицы Якоби должен быть близок к нулю
3. Одно из собственных значений матрицы Якоби должно быть близко нулю

Также необходимо проверить, что полученные точки являются точками поворота, а не ветвления: в матрице Якоби вычеркиваем один столбец и заменяем его на частные производные по параметру **p4**, подставляем все значения и проверяем, что определитель полученной матрицы не равен нулю.

В приложении приведен код программы с реализацией данных проверок.

4 Результаты работы программы

```
p4 = 1.000000e+00
x1 = 2.296225e-04 x1 = 2.296225e-04 x1 = -4.611574e-04

p4 = 1.100000e+00
x1 = -5.538053e-05 x1 = 7.200466e-05 x1 = 2.378996e-02
x2 = 1.131154e+00 x3 = 3.428793e-05 p6 = 2.275275e+00
x2 = 9.758213e-01 x3 = 1.132855e-02 p6 = 2.991050e+01

p4 = 1.200000e+00
x1 = -3.832125e-05 x1 = 5.496644e-05 x1 = 4.543393e-02
x2 = 1.179378e+00 x3 = 2.498474e-05 p6 = 2.340153e+00
x2 = 9.539424e-01 x3 = 2.065178e-02 p6 = 9.684935e+01

p4 = 1.300000e+00
x1 = -3.106441e-05 x1 = 4.773154e-05 x1 = 6.519572e-02
x2 = 1.212459e+00 x3 = 2.075284e-05 p6 = 2.361309e+00
x2 = 9.340580e-01 x3 = 2.834596e-02 p6 = 1.832033e+02

p4 = 1.400000e+00
x1 = -2.691505e-05 x1 = 4.359485e-05 x1 = 8.331062e-02
x2 = 1.237461e+00 x3 = 1.816452e-05 p6 = 2.362952e+00
x2 = 9.158484e-01 x3 = 3.471276e-02 p6 = 2.774243e+02

p4 = 1.500000e+00
x1 = -2.420245e-05 x1 = 4.088966e-05 x1 = 9.997624e-02
x2 = 1.257234e+00 x3 = 1.635586e-05 p6 = 2.354354e+00
x2 = 8.990993e-01 x3 = 3.999050e-02 p6 = 3.727117e+02

p4 = 1.600000e+00
x1 = -2.228721e-05 x1 = 3.897874e-05 x1 = 1.153598e-01
x2 = 1.273291e+00 x3 = 1.499182e-05 p6 = 2.340034e+00
x2 = 8.836378e-01 x3 = 4.436916e-02 p6 = 4.651303e+02

p4 = 1.700000e+00
x1 = -2.086596e-05 x1 = 3.755986e-05 x1 = 1.296038e-01
x2 = 1.286559e+00 x3 = 1.391106e-05 p6 = 2.322471e+00
x2 = 8.693192e-01 x3 = 4.800141e-02 p6 = 5.524949e+02

p4 = 1.800000e+00
x1 = -1.977426e-05 x1 = 3.646923e-05 x1 = 1.428303e-01
x2 = 1.297654e+00 x3 = 1.302473e-05 p6 = 2.303118e+00
x2 = 8.560201e-01 x3 = 5.101082e-02 p6 = 6.336964e+02

p4 = 1.900000e+00
x1 = -1.891450e-05 x1 = 3.560960e-05 x1 = 1.551445e-01
x2 = 1.307010e+00 x3 = 1.227917e-05 p6 = 2.282866e+00
x2 = 8.436345e-01 x3 = 5.349811e-02 p6 = 7.082861e+02

p4 = 2.000000e+00
x1 = -1.822469e-05 x1 = 3.491923e-05 x1 = 1.666377e-01
x2 = 1.314950e+00 x3 = 1.163974e-05 p6 = 2.262276e+00
x2 = 8.320709e-01 x3 = 5.554592e-02 p6 = 7.762166e+02

p4 = 2.000000e+00
```

```
x1 = -1.822469e-05 x1 = 3.491923e-05 x1 = 1.666377e-01
x2 = 1.314950e+00 x3 = 1.163974e-05 p6 = 2.262276e+00
x2 = 8.320709e-01 x3 = 5.554592e-02 p6 = 7.762166e+02

p4 = 3.000000e+00
x1 = -1.542839e-05 x1 = 3.209895e-05 x1 = 2.499608e-01
x2 = 1.351694e+00 x3 = 8.024738e-06 p6 = 2.077173e+00
x2 = 7.480643e-01 x3 = 6.249020e-02 p6 = 1.163471e+03

p4 = 4.000000e+00
x1 = -1.511175e-05 x1 = 3.174281e-05 x1 = 2.999505e-01
x2 = 1.356184e+00 x3 = 6.348561e-06 p6 = 1.943201e+00
x2 = 6.974023e-01 x3 = 5.999010e-02 p6 = 1.255223e+03

p4 = 5.000000e+00
x1 = -1.546367e-05 x1 = 3.204575e-05 x1 = 3.332736e-01
x2 = 1.350683e+00 x3 = 5.340958e-06 p6 = 1.845085e+00
x2 = 6.634098e-01 x3 = 5.554560e-02 p6 = 1.238275e+03

p4 = 6.000000e+00
x1 = -1.607331e-05 x1 = 3.259820e-05 x1 = 3.570729e-01
x2 = 1.341701e+00 x3 = 4.656886e-06 p6 = 1.770072e+00
x2 = 6.389422e-01 x3 = 5.101041e-02 p6 = 1.183125e+03

p4 = 7.000000e+00
x1 = -1.679783e-05 x1 = 3.325775e-05 x1 = 3.749198e-01
x2 = 1.331635e+00 x3 = 4.157218e-06 p6 = 1.710582e+00
x2 = 6.204275e-01 x3 = 4.686497e-02 p6 = 1.116653e+03

p4 = 8.000000e+00
x1 = -1.757607e-05 x1 = 3.396343e-05 x1 = 3.887984e-01
x2 = 1.321463e+00 x3 = 3.773715e-06 p6 = 1.662013e+00
x2 = 6.058813e-01 x3 = 4.319982e-02 p6 = 1.049452e+03

p4 = 9.000000e+00
x1 = -1.837849e-05 x1 = 3.468581e-05 x1 = 3.998993e-01
x2 = 1.311601e+00 x3 = 3.468581e-06 p6 = 1.621436e+00
x2 = 5.941132e-01 x3 = 3.998993e-02 p6 = 9.856478e+02

p4 = 1.000000e+01
x1 = -1.918969e-05 x1 = 3.540951e-05 x1 = 4.089800e-01
x2 = 1.302215e+00 x3 = 3.219047e-06 p6 = 1.586900e+00
x2 = 5.843653e-01 x3 = 3.718000e-02 p6 = 9.266651e+02

p4 = 1.000000e+01
x1 = -1.918969e-05 x1 = 3.540951e-05 x1 = 4.089800e-01
x2 = 1.302215e+00 x3 = 3.219047e-06 p6 = 1.586900e+00
x2 = 5.843653e-01 x3 = 3.718000e-02 p6 = 9.266651e+02

p4 = 2.000000e+01
x1 = -2.696682e-05 x1 = 4.190594e-05 x1 = 4.521682e-01
x2 = 1.233973e+00 x3 = 1.995521e-06 p6 = 1.397336e+00
x2 = 5.345084e-01 x3 = 2.153182e-02 p6 = 5.591702e+02

p4 = 3.000000e+01
x1 = -3.400617e-05 x1 = 4.692934e-05 x1 = 4.674280e-01
x2 = 1.193598e+00 x3 = 1.513850e-06 p6 = 1.311747e+00
x2 = 5.125811e-01 x3 = 1.507832e-02 p6 = 3.932122e+02

p4 = 4.000000e+01
x1 = -4.064265e-05 x1 = 5.081503e-05 x1 = 4.751955e-01
x2 = 1.166034e+00 x3 = 1.239391e-06 p6 = 1.259644e+00
x2 = 4.981465e-01 x3 = 1.159013e-02 p6 = 3.007863e+02
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p4 = 5.000000e+01
x1 = -4.712664e-05 x1 = 5.381312e-05 x1 = 4.798782e-01
x2 = 1.145406e+00 x3 = 1.055159e-06 p6 = 1.223197e+00
x2 = 4.867968e-01 x3 = 9.409377e-03 p6 = 2.421209e+02

p4 = 6.000000e+01
x1 = -5.362214e-05 x1 = 5.608721e-05 x1 = 4.829937e-01
x2 = 1.129036e+00 x3 = 9.194625e-07 p6 = 1.195569e+00
x2 = 4.770143e-01 x3 = 7.917930e-03 p6 = 2.016274e+02

p4 = 7.000000e+01
x1 = 5.775365e-05 x1 = -6.024587e-05 x1 = 4.852045e-01
x2 = 1.115523e+00 x3 = 8.134317e-07 p6 = 1.173515e+00
x2 = 4.681367e-01 x3 = 6.833866e-03 p6 = 1.720110e+02

p4 = 8.000000e+01
x1 = 5.890190e-05 x1 = -6.708770e-05 x1 = 4.868459e-01
x2 = 1.104057e+00 x3 = 7.271840e-07 p6 = 1.155280e+00
x2 = 4.598284e-01 x3 = 6.010443e-03 p6 = 1.494140e+02

p4 = 9.000000e+01
x1 = 5.960510e-05 x1 = -7.422117e-05 x1 = 4.881059e-01
x2 = 1.094134e+00 x3 = 6.550011e-07 p6 = 1.139819e+00
x2 = 4.519016e-01 x3 = 5.363801e-03 p6 = 1.316078e+02

p4 = 1.000000e+02
x1 = 5.992564e-05 x1 = -8.170907e-05 x1 = 4.890980e-01
x2 = 1.085421e+00 x3 = 5.933232e-07 p6 = 1.126469e+00
x2 = 4.442427e-01 x3 = 4.842554e-03 p6 = 1.172160e+02

p4 = 1.000000e+02
x1 = 5.992564e-05 x1 = -8.170907e-05 x1 = 4.890980e-01
x2 = 1.085421e+00 x3 = 5.933232e-07 p6 = 1.126469e+00
x2 = 4.442427e-01 x3 = 4.842554e-03 p6 = 1.172160e+02

p4 = 2.000000e+02
x1 = 5.178628e-05 x1 = -1.858662e-04 x1 = 4.931049e-01
x2 = 1.034399e+00 x3 = 2.576432e-07 p6 = 1.051764e+00
x2 = 3.735675e-01 x3 = 2.453258e-03 p6 = 5.080235e+01

p4 = 3.000000e+02
x1 = 3.984376e-05 x1 = -3.603206e-04 x1 = 4.939129e-01
x2 = 1.013663e+00 x3 = 1.323713e-07 p6 = 1.022783e+00
x2 = 3.060913e-01 x3 = 1.640907e-03 p6 = 2.803760e+01

p4 = 4.000000e+02
x1 = 3.116581e-05 x1 = -6.124341e-04 x1 = 4.939709e-01
x2 = 1.003870e+00 x3 = 7.772023e-08 p6 = 1.009434e+00
x2 = 2.393651e-01 x3 = 1.231848e-03 p6 = 1.652041e+01

p4 = 5.000000e+02
x1 = 2.528165e-05 x1 = -9.419647e-04 x1 = 4.937729e-01
x2 = 9.983474e-01 x3 = 5.046238e-08 p6 = 1.002119e+00
x2 = 1.728951e-01 x3 = 9.855746e-04 p6 = 9.555413e+00

p4 = 6.000000e+02
x1 = 2.116873e-05 x1 = -1.348052e-03 x1 = 4.934839e-01
x2 = 9.946758e-01 x3 = 3.522252e-08 p6 = 9.974264e-01
x2 = 1.065159e-01 x3 = 8.211047e-04 p6 = 4.880446e+00

p4 = 7.000000e+02
x1 = 1.816874e-05 x1 = -1.830133e-03 x1 = 4.931751e-01
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x2 = 9.919011e-01 x3 = 2.591831e-08 p6 = 9.940146e-01
x2 = 4.015655e-02 x3 = 7.035309e-04 p6 = 1.518508e+00

p4 = 8.000000e+02
x1 = 1.589556e-05 x1 = -2.387848e-03 x1 = 4.928820e-01
x2 = 9.896037e-01 x3 = 1.984464e-08 p6 = 9.912914e-01
x2 = -2.621842e-02 x3 = 6.153333e-04 p6 = -1.021372e+00

p4 = 9.000000e+02
x1 = 1.411796e-05 x1 = -3.020925e-03 x1 = 4.926241e-01
x2 = 9.875799e-01 x3 = 1.566921e-08 p6 = 9.889678e-01
x2 = -9.262872e-02 x3 = 5.467527e-04 p6 = -3.012932e+00

p4 = 1.000000e+03
x1 = 1.269161e-05 x1 = -3.729114e-03 x1 = 4.924134e-01
x2 = 9.857224e-01 x3 = 1.267893e-08 p6 = 9.868905e-01
x2 = -1.590861e-01 x3 = 4.919215e-04 p6 = -4.620854e+00

p4 = 1.100000e+03
x1 = 1.152256e-05 x1 = -4.512143e-03 x1 = 4.922571e-01
x2 = 9.839711e-01 x3 = 1.046554e-08 p6 = 9.849725e-01
x2 = -2.255979e-01 x3 = 4.471000e-04 p6 = -5.950154e+00

p4 = 1.200000e+03
x1 = 1.054734e-05 x1 = -5.369709e-03 x1 = 4.921600e-01
x2 = 9.822901e-01 x3 = 8.782136e-09 p6 = 9.831617e-01
x2 = -2.921690e-01 x3 = 4.097918e-04 p6 = -7.070956e+00

p4 = 1.300000e+03
x1 = 9.721647e-06 x1 = -6.301460e-03 x1 = 4.921253e-01
x2 = 9.806572e-01 x3 = 7.472442e-09 p6 = 9.814255e-01
x2 = -3.588025e-01 x3 = 3.782670e-04 p6 = -8.031870e+00

p4 = 1.400000e+03
x1 = 9.013637e-06 x1 = -7.306993e-03 x1 = 4.921552e-01
x2 = 9.790581e-01 x3 = 6.433716e-09 p6 = 9.797426e-01
x2 = -4.255005e-01 x3 = 3.512885e-04 p6 = -8.867653e+00

p4 = 1.500000e+03
x1 = 8.399885e-06 x1 = -8.385854e-03 x1 = 4.922510e-01
x2 = 9.774833e-01 x3 = 5.596192e-09 p6 = 9.780987e-01
x2 = -4.922644e-01 x3 = 3.279487e-04 p6 = -9.603813e+00
```

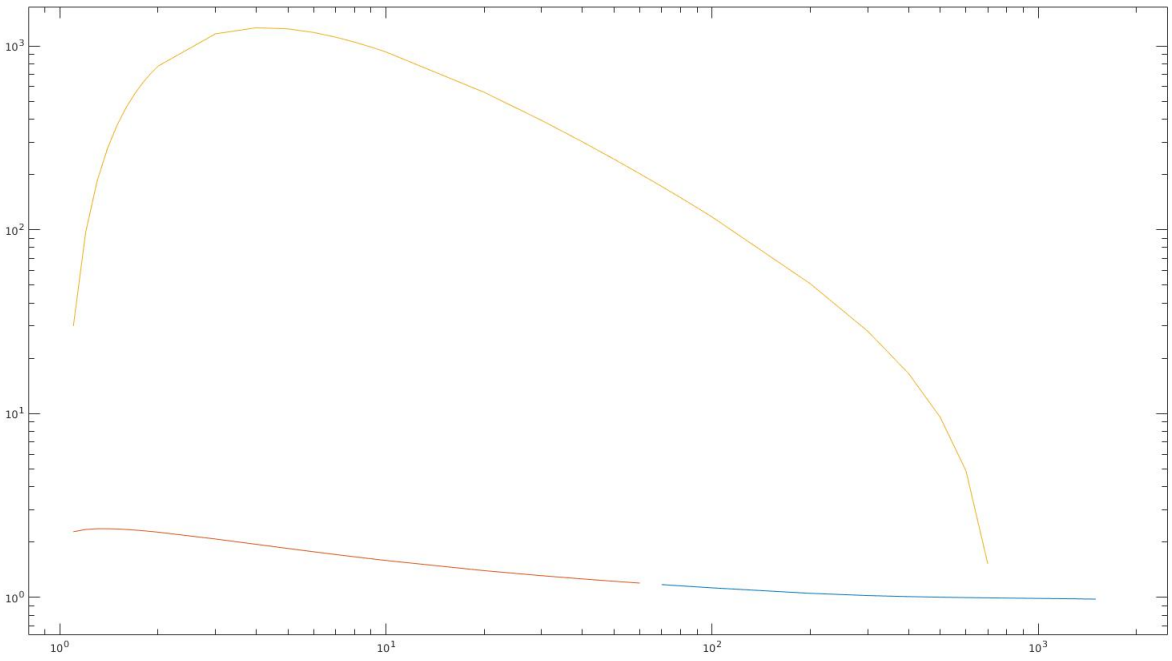

5 Результаты работы блока проверки

```
p4 = 1.100000
1:
 det = 0.051595
eigenvalues: 79.035395 -8850.874123 -0.000000
System: 0.000000, 0.000000, , 0.000000
detcheck: -32.328115

2:
 det = -4.753448
eigenvalues: 13740.356714 -19535.618289 0.000000
System: -0.000002, -0.000326, 0.000000
detcheck: -8887.142126

p4 = 1.200000
1:
 det = 0.150740
eigenvalues: 39.544679 -12021.331986 -0.000000
System: 0.000000, 0.000000, , 0.000000
detcheck: -27.423629

2:
 det = -10.985002
eigenvalues: 17269.420917 -28340.123947 0.000000
System: 0.000002, -0.000623, 0.000000
detcheck: -17775.862340

p4 = 1.300000
1:
 det = 0.243875
eigenvalues: 26.227793 -14211.475248 -0.000001
System: 0.000000, 0.000001, , 0.000000
detcheck: -25.941850
```

```
2:
 det = -7.068510
eigenvalues: 19163.083596 -35056.622866 0.000000
System: -0.000004, -0.000706, 0.000000
detcheck: -26664.563443

p4 = 1.400000
1:
 det = 0.120861
eigenvalues: 19.506086 -15870.574892 -0.000000
System: 0.000000, 0.000001, , 0.000000
detcheck: -25.544747

2:
 det = -18.321732
eigenvalues: 20270.530901 -40586.189767 0.000000
System: -0.000002, 0.000169, -0.000000
detcheck: -35553.252901

p4 = 1.500000
1:
 det = -0.108941
eigenvalues: 15.429315 -17184.163091 0.000000
System: -0.000000, -0.000001, , 0.000000
detcheck: -25.656789

2:
 det = 24.590462
eigenvalues: 20920.511382 -45304.765699 -0.000000
System: -0.000000, 0.000382, -0.000000
detcheck: -44441.923248

p4 = 1.600000
1:
 det = 0.216833
eigenvalues: 12.676766 -18251.588045 -0.000001
System: 0.000000, 0.000000, , 0.000000
detcheck: -26.059780

2:
 det = 170.461503
eigenvalues: 21278.983945 -49418.807326 -0.000000
System: 0.000012, 0.001182, -0.000000
detcheck: -53330.572350

p4 = 1.700000
1:
 det = -0.009814
eigenvalues: 10.681390 -19133.988994 0.000000
System: 0.000000, 0.000000, , -0.000000
detcheck: -26.651009

2:
 det = 38.130305
eigenvalues: 21441.728099 -53058.781190 -0.000000
System: 0.000001, 0.000296, -0.000000
detcheck: -62219.223673

p4 = 1.800000
1:
 det = -0.408093
eigenvalues: 9.159510 -19872.098171 0.000002
System: -0.000000, -0.000001, , -0.000000
```

```
detcheck: -27.375185

2:
 det = -137.328879
eigenvalues: 21468.713662 -56314.404975 0.000000
System: -0.000013, -0.000729, 0.000000
detcheck: -71107.859441

p4 = 1.900000
1:
 det = 0.272557
eigenvalues: 7.953478 -20494.661144 -0.000002
System: 0.000000, 0.000001, , 0.000000
detcheck: -28.199677

2:
 det = 267.482603
eigenvalues: 21399.591879 -59250.992415 -0.000000
System: 0.000001, 0.000780, -0.000000
detcheck: -79996.449430

p4 = 2.000000
1:
 det = -0.283135
eigenvalues: 6.968469 -21023.097334 0.000002
System: -0.000000, -0.000001, , 0.000000
detcheck: -29.103878

2:
 det = 560.181153
eigenvalues: 21261.610655 -61918.096095 -0.000000
System: 0.000001, 0.002357, -0.000000
detcheck: -88885.030974

p4 = 2.000000
1:
 det = -0.283135
eigenvalues: 6.968469 -21023.097334 0.000002
System: -0.000000, -0.000001, , 0.000000
detcheck: -29.103878

2:
 det = 560.181153
eigenvalues: 21261.610655 -61918.096095 -0.000000
System: 0.000001, 0.002357, -0.000000
detcheck: -88885.030974

p4 = 3.000000
1:
 det = -0.537817
eigenvalues: 1.984879 -23469.848574 0.000012
System: -0.000000, -0.000001, , -0.000000
detcheck: -40.799613

2:
 det = -185.927167
eigenvalues: 18607.701043 -79589.701414 0.000000
System: 0.000011, 0.001712, 0.000000
detcheck: -177770.097504

p4 = 4.000000
1:
 det = 1.158111
```

```
eigenvalues: 0.000142 -23769.744374 -0.343480
System: 0.000000, 0.000002, , 0.000000
detcheck: -55.682944

2:
 det = 683.735601
eigenvalues: 15952.877156 -89112.889499 -0.000000
System: 0.000023, -0.000138, 0.000000
detcheck: -266653.466210

p4 = 5.000000
1:
 det = -1.044646
eigenvalues: -0.000022 -23404.439230 -2.007542
System: -0.000000, -0.000004, , 0.000000
detcheck: -73.142673

2:
 det = -515.850727
eigenvalues: 13839.060814 -95103.178093 0.000000
System: -0.000015, -0.002852, -0.000000
detcheck: -355535.243760

p4 = 6.000000
1:
 det = -1.109873
eigenvalues: -0.000014 -22807.409570 -3.406091
System: -0.000000, -0.000004, , -0.000000
detcheck: -93.020620

2:
 det = -2507.079460
eigenvalues: 12180.147701 -99220.378913 0.000002
System: -0.000048, -0.003858, 0.000000
detcheck: -444415.394598

p4 = 7.000000
1:
 det = -1.767959
eigenvalues: -0.000017 -22138.279034 -4.671798
System: -0.000000, -0.000002, , 0.000000
detcheck: -115.247318

2:
 det = -3335.834166
eigenvalues: 10860.116035 -102221.448190 0.000003
System: -0.000050, -0.002041, 0.000000
detcheck: -533293.883168

p4 = 8.000000
1:
 det = 1.858326
eigenvalues: 0.000015 -21462.172086 -5.861601
System: 0.000000, 0.000006, , -0.000000
detcheck: -139.782335

2:
 det = 174.586882
eigenvalues: 9790.531113 -104502.938510 -0.000000
System: 0.000018, -0.002196, 0.000000
detcheck: -622170.656136

p4 = 9.000000
```

```
1:
 det = -0.459851
eigenvalues: -0.000003 -20806.784507 -7.003950
System: -0.000000, -0.000001, , 0.000000
detcheck: -166.597953

2:
 det = -1816.968670
eigenvalues: 8908.681701 -106293.190580 0.000002
System: -0.000030, -0.001314, 0.000000
detcheck: -711045.909060

p4 = 10.000000
1:
 det = 0.251571
eigenvalues: 0.000002 -20183.162482 -8.114671
System: 0.000000, -0.000000, , -0.000000
detcheck: -195.673002

2:
 det = -3733.112529
eigenvalues: 8170.248615 -107733.027147 0.000004
System: 0.000001, 0.000222, 0.000000
detcheck: -799919.535272

p4 = 10.000000
1:
 det = 0.251571
eigenvalues: 0.000002 -20183.162482 -8.114671
System: 0.000000, -0.000000, , -0.000000
detcheck: -195.673002

2:
 det = -3733.112529
eigenvalues: 8170.248615 -107733.027147 0.000004
System: 0.000001, 0.000222, 0.000000
detcheck: -799919.535272

p4 = 20.000000
1:
 det = 8.000844
eigenvalues: 0.000028 -15655.227970 -18.580925
System: 0.000000, 0.000012, , -0.000000
detcheck: -607.811190

2:
 det = -7944.330932
eigenvalues: 4450.741337 -114156.163582 0.000016
System: -0.000048, -0.002502, -0.000000
detcheck: -1688567.074908

p4 = 30.000000
1:
 det = 3.583020
eigenvalues: 0.000010 -12984.965918 -28.725684
System: 0.000000, 0.000017, , -0.000000
detcheck: -1234.929952

2:
 det = 13565.670190
eigenvalues: 3049.099370 -116070.231670 -0.000038
System: 0.000008, -0.000526, 0.000000
detcheck: -2577056.138952
```

```
p4 = 40.000000
1:
 det = 18.916708
eigenvalues: 0.000044 -11168.495089 -38.796252
System: 0.000000, -0.000001, , -0.000000
detcheck: -2071.617169

2:
 det = -6176.577625
eigenvalues: 2311.614176 -116817.013054 0.000023
System: 0.000004, 0.000683, 0.000000
detcheck: -3465391.723022

p4 = 50.000000
1:
 det = -55.888667
eigenvalues: -0.000117 -9814.178998 -48.838055
System: -0.000000, -0.000031, , 0.000000
detcheck: -3114.072672

2:
 det = 28444.601194
eigenvalues: 1854.665078 -117090.266880 -0.000131
System: 0.000015, 0.002649, -0.000000
detcheck: -4353576.227148

p4 = 60.000000
1:
 det = -65.509040
eigenvalues: -0.000127 -8743.520031 -58.865722
System: -0.000000, -0.000002, , -0.000000
detcheck: -4359.336708

2:
 det = 32616.044839
eigenvalues: 1542.267200 -117124.974691 -0.000181
System: 0.000070, 0.002519, -0.000000
detcheck: -5241614.913618

p4 = 70.000000
1:
 det = -4.745887
eigenvalues: -0.000009 -7863.147750 -68.885403
System: -0.000000, -0.000019, , -0.000000
detcheck: -5805.016509

2:
 det = 12465.796329
eigenvalues: 1314.085217 -117022.760680 -0.000081
System: 0.000003, -0.000120, 0.000000
detcheck: -6129511.604702

p4 = 80.000000
1:
 det = 24.313606
eigenvalues: 0.000043 -7119.086486 -78.900134
System: 0.000000, 0.000036, , -0.000000
detcheck: -7449.159474

2:
 det = 11793.687375
eigenvalues: 1139.260640 -116834.709178 -0.000089
```

```
System: 0.000025, 0.001868, 0.000000
detcheck: -7017269.553774

p4 = 90.000000
1:
 det = -181.308442
eigenvalues: -0.000315 -6477.756811 -88.911585
System: -0.000000, 0.000013, , -0.000000
detcheck: -9290.185148

2:
 det = -14100.206055
eigenvalues: 1000.361477 -116589.357890 0.000121
System: -0.000017, 0.001654, 0.000000
detcheck: -7904893.383114

p4 = 100.000000
1:
 det = -337.563085
eigenvalues: -0.000577 -5916.977532 -98.920755
System: -0.000000, -0.000017, , -0.000000
detcheck: -11326.840160

2:
 det = -57903.475184
eigenvalues: 886.805913 -116303.863079 0.000561
System: -0.000052, -0.000540, 0.000000
detcheck: -8792386.914992

p4 = 100.000000
1:
 det = -337.563085
eigenvalues: -0.000577 -5916.977532 -98.920755
System: -0.000000, -0.000017, , -0.000000
detcheck: -11326.840160

2:
 det = -57903.475184
eigenvalues: 886.805913 -116303.863079 0.000561
System: -0.000052, -0.000540, 0.000000
detcheck: -8792386.914992

p4 = 200.000000
1:
 det = 73.981504
eigenvalues: 0.000137 -2712.919979 -198.963080
System: 0.000000, 0.000093, , -0.000000
detcheck: -42350.683289

2:
 det = -70485.547157
eigenvalues: 316.505324 -112568.463036 0.001978
System: -0.000027, -0.000430, 0.000000
detcheck: -17661002.177274

p4 = 300.000000
1:
 det = 857.198720
eigenvalues: 0.001878 -1526.782515 -298.979887
System: 0.000000, 0.000137, , -0.000000
detcheck: -92881.609471

2:
```

```
 det = -37026.463548
eigenvalues: 58.927955 -108363.833773 0.005798
System: 0.000004, 0.001670, -0.000000
detcheck: -26520907.942914

p4 = 400.000000
1:
 det = -49.256467
eigenvalues: -0.000115 -1071.198625 -398.992021
System: 0.000000, 0.000182, , -0.000000
detcheck: -163220.637890

2:
 det = 150272.358530
eigenvalues: 0.012104 -104055.212407 -119.308753
System: 0.000052, 0.003260, -0.000000
detcheck: -35376075.621554

p4 = 500.000000
1:
 det = -7.543190
eigenvalues: -0.000017 -901.180853 -499.004073
System: 0.000000, 0.000039, , -0.000000
detcheck: -253499.949792

2:
 det = -227686.063717
eigenvalues: -0.008599 -99716.014621 -265.529774
System: -0.000043, -0.000924, 0.000000
detcheck: -44230504.196514

p4 = 600.000000
1:
 det = -636.494239
eigenvalues: -0.001243 -855.111420 -599.018136
System: 0.000000, -0.000042, , -0.000000
detcheck: -363759.294020

2:
 det = 235171.866099
eigenvalues: 0.006233 -95370.716972 -395.628183
System: 0.000010, -0.000534, -0.000000
detcheck: -53088169.717494

p4 = 700.000000
1:
 det = -735.804352
eigenvalues: -0.001211 -869.179463 -699.035861
System: -0.000000, -0.000004, , 0.000000
detcheck: -494011.096809

2:
 det = 257056.713131
eigenvalues: 0.005469 -91029.909619 -516.383982
System: 0.000025, 0.000359, -0.000000
detcheck: -61953092.003630

p4 = 800.000000
1:
 det = -1550.862386
eigenvalues: -0.002120 -915.287310 -799.059121
System: -0.000000, -0.000008, , 0.000000
detcheck: -644259.730990
```

```
2:
 det = -276795.295653
eigenvalues: -0.005058 -86698.879137 -631.196299
System: -0.000020, 0.000104, 0.000000
detcheck: -70829270.304912

p4 = 900.000000
1:
 det = -2432.708083
eigenvalues: -0.002762 -979.781566 -899.090512
System: -0.000000, -0.000015, , 0.000000
detcheck: -814506.921879

2:
 det = 477780.833944
eigenvalues: 0.007817 -82380.534337 -741.942203
System: 0.000030, -0.000744, -0.000000
detcheck: -79720665.470850

p4 = 1000.000000
1:
 det = 2193.951586
eigenvalues: 0.002080 -1055.465120 -999.134090
System: -0.000000, 0.000077, , 0.000000
detcheck: -1004753.416092

2:
 det = -75377.927352
eigenvalues: -0.001136 -78076.686509 -849.715206
System: -0.000010, -0.000169, -0.000000
detcheck: -88631290.351604

p4 = 1100.000000
1:
 det = 252.225646
eigenvalues: 0.000202 -1138.282881 -1099.196826
System: -0.000000, 0.000050, , 0.000000
detcheck: -1214999.557821

2:
 det = -195352.362110
eigenvalues: -0.002772 -73788.432573 -955.198218
System: -0.000037, -0.000627, -0.000000
detcheck: -97565071.609590

p4 = 1200.000000
1:
 det = -1281.755213
eigenvalues: -0.000872 -1225.815863 -1199.292139
System: 0.000000, 0.000008, , -0.000000
detcheck: -1445245.518184

2:
 det = 131752.849986
eigenvalues: 0.001790 -69516.517594 -1058.813065
System: 0.000010, 0.000142, 0.000000
detcheck: -106525935.480552

p4 = 1300.000000
1:
 det = -1902.451648
eigenvalues: -0.001112 -1316.539912 -1299.450421
```

```
System: 0.000000, 0.000017, , -0.000000
detcheck: -1695491.387991

2:
 det = 670809.135131
eigenvalues: 0.008855 -65261.471084 -1160.815440
System: 0.000056, 0.000207, -0.000000
detcheck: -115517779.470986

p4 = 1400.000000
1:
 det = -1352.888899
eigenvalues: -0.000686 -1409.399378 -1399.763909
System: -0.000000, 0.000032, , 0.000000
detcheck: -1965737.210737

2:
 det = 99318.101355
eigenvalues: 0.001290 -61023.684536 -1261.341165
System: 0.000028, 0.000724, 0.000000
detcheck: -124544479.576008

p4 = 1500.000000
1:
 det = -82.549050
eigenvalues: -0.000037 -1502.984883 -1501.000915
System: -0.000000, 0.000026, , 0.000000
detcheck: -2255983.012017

2:
 det = -175005.788930
eigenvalues: -0.002265 -56803.443416 -1360.434530
System: -0.000000, 0.000510, 0.000000
detcheck: -133609828.074132
```

6 Выводы

Все проверки прошли успешно, следовательно можно утверждать, что полученные значения верны.

7 Приложение

7.1 Исходный код

```
clear all
clear global variables
syms x1 x2 x3 p4 p6

global eq x2val x3val

global det11 det12 det13 det21 det22 det23 det31 det32 det33

global p1 p2 p3 p5

global x1 x2 x3 p4 p6 p6eq

p1 = double(8.4e-6);
p2 = 6.6667e-4;
p2opp = 66667;
```

```
p3 = 1.7778e-5;
p3opp = 177780;
p5 = 2;

x2val = (x1 * x1 + p2 * p4 * x1 - x1) / (p1 - x1);
x3val = x1 / (1 + p4);
%p6 = (p1 * x2 + x1 * x2 - p5 * x3) / p3 * p4 + x2;

det11 = -x2*p2opp + 1*p2opp - 2*x1*p2opp - p4;
det12 = p1 * p2opp - x1 * p2opp;
det13 = 0;
det21 = -x2*p3opp;
det22 = - p1 * p3opp - x1 * p3opp - p4;
det23 = p5*p3opp;
det31 = 1;
det32 = 0;
det33 = - 1 - p4;

det11 = subs(det11, x2, x2val);
det21 = subs(det21, x2, x2val);

res = det ( [det11 det12 det13; det21 det22 det23; det31 det32 det33] );

p6eq = (-p1*x2 + x1*x2 - p5*x3 + p4 * p3 * (p6 - x2))*p3opp == 0;

p6val = solve(p6eq, p6);

eq = res == 0;

global fileID fileIDcheck fileIDplot1 fileIDplot2 fileIDplot3;

fileIDplot3 = fopen('forplot3.txt', 'w');
fileID = fopen('results_p6_auto.txt', 'w');
fileIDcheck = fopen('check.txt', 'w');
fileIDplot1 = fopen('forplot1.txt', 'w');
fileIDplot2 = fopen('forplot2.txt', 'w');



forrange(1.0, 2.0, 0.1);
forrange(2.0, 10.0, 1.0);
forrange(10.0, 100.0, 10.0);
forrange(100.0, 1500.0, 100.0);

fclose(fileID);
fclose(fileIDcheck);
fclose(fileIDplot1);
fclose(fileIDplot2);
fclose(fileIDplot3);

%fid=fopen('forplot2.txt');
%s = textscan(fid,'%f %f','headerlines',23);
%fclose(fid);
%x=s{1};
%y=s{2};

%loglog(x, y);
%hold on;


%fid=fopen('forplot3.txt');
%s=textscan(fid,'%f %f');
%fclose(fid);
```

```
%x=s{1};
%y=s{2};

%loglog(x, y);
%hold off;

A = load('forplot1.txt');
B = load('forplot2.txt');
C = load('forplot3.txt');

%plot(B(:,1),B(:,2));
%hold on;
%plot(C(:,1),C(:,2));
%hold off;


loglog(A(:,1), A(:,2));
hold on;
loglog(B(:,1),B(:,2));
loglog(C(:,1),C(:,2));
hold off;



function[x11, x12, x13, x2tmp, x3tmp] = subsp4(i)
global p4 x1 eq x2val x3val;
inner = subs(eq, p4, i);
solution = solve(inner, x1);
x11 = solution(1);
x12 = solution(2);
x13 = solution(3);

x2tmp = subs(x2val, p4, i);
x3tmp = subs(x3val, p4, i);
%p6tmp = subs(p6, p4, i);
end

function[p6res] = subsx1(x1in, x2tmp, x3tmp, p6tmp)
global fileID fileIDcheck x1 x2 x3 p6;
if (isAlways(x1in > 0) == true)
          x2in = subs(x2tmp, x1, x1in);
          x3in = subs(x3tmp, x1, x1in);
          p6in = subs(p6tmp, x1, x1in);
          p6in = subs(p6in, x2, x2in);
          p6in = subs(p6in, x3, x3in);

          p6res = solve(p6in, p6);
          %p6res = p6in;

          fprintf(fileID, 'x2 = %e x3 = %e p6 = %e\n', x2in, x3in, p6res(1));
          fprintf(fileIDcheck, '%e %e %e %e\n', x1in, x2in, x3in, p6res(1));
          %fprintf(fileIDplot1, '%e %e \n', i, p6res);

else
    p6res = -1;
end
end

function forrange(left, right, step)

global fileIDcheck fileID fileIDplot1 fileIDplot2 fileIDplot3 p6 p6eq p4;
for i = left: step: right

```

```
    fprintf(fileID, 'p4 = %e \n', i);
    fprintf(fileIDcheck, '%e\n', i);

    p6eqp4 = subs(p6eq, p4, i);
    %p6eqp4 = subs(p6, p4, i);

    [x11, x12, x13, x2tmp, x3tmp] = subsp4(i);

    fprintf(fileID, 'x1 = %e x1 = %e x1 = %e\n', x11, x12, x13);

    p6res = subsx1(x11, x2tmp, x3tmp, p6eqp4);

    fprintf(fileIDplot1, '%e %e \n', i, p6res);

    p6res = subsx1(x12, x2tmp, x3tmp, p6eqp4);
    fprintf(fileIDplot2, '%e %e \n', i, p6res);

    p6res = subsx1(x13, x2tmp, x3tmp, p6eqp4);
    fprintf(fileIDplot3, '%e %e \n', i, p6res);

    fprintf(fileID, '\n');
end
end
```

7.2 Код блока проверки

```
clear all
syms x1 x2 x3 p1 p2 p3 p4 p5 p6

p1 = double(8.4e-6);
p2 = 6.6667e-4;
p2opp = 66667;
p3 = 1.7778e-5;
p3opp = 177780;
p5 = 2;

det11 = -x2*p2opp + 1*p2opp - 2*x1*p2opp - p4;
det12 = p1 * p2opp - x1 * p2opp;
det13 = 0;
det21 = -x2*p3opp;
det22 = - p1 * p3opp - x1 * p3opp - p4;
det23 = p5*p3opp;
det31 = 1;
det32 = 0;
det33 = - 1 - p4;

res =  ( [det11 det12 det13; det21 det22 det23; det31 det32 det33] );
matrix = [det11 det12 det13; det21 det22 det23; det31 det32 det33];
detcheck = det ( [-1 det12 det13; 0 det22 det23; 0 det32 det33] );

eq1 = (p1*x2 - x1*x2 + x1 - x1^2) / p2 - p4*x1;
eq2 = (-p1*x2 - x1*x2 + p5*x3)/p3 + p4 * (p6 - x2);
eq3 = x1 - x3 - p4*x3;


fid = fopen('check.txt', 'r');
fres = fopen('check_res.txt', 'w');

while ~feof(fid)
    i = fscanf(fid, "%e", 1);

    x11 = fscanf(fid, "%e", 1);
```

```
    x21 = fscanf(fid, "%e", 1);
    x31 = fscanf(fid, "%e", 1);
    p61 = fscanf(fid, "%e", 1);

    x12 = fscanf(fid, "%e", 1);
    x22 = fscanf(fid, "%e", 1);
    x32 = fscanf(fid, "%e", 1);
    p62 = fscanf(fid, "%e", 1);
    %fscanf(fid, '%f %f %f %f\n', x11, x21, x31, p61);
    %fscanf(fid, '%f %f %f %f\n', x12, x22, x32, p62);
    check1 = subs(res, p4, i);
    check1 = subs(check1, x1, x11);
    check1 = subs(check1, x2, x21);
    check1 = subs(check1, x3, x31);
    check1 = subs(check1, p6, p61);
    check1tmp = det(check1);
    fprintf(fres, 'p4 = %f \n', i);
    fprintf(fres, '1:\n det = %f\n', check1tmp);
    eigenvalues = eig(check1);
    fprintf(fres, 'eigenvalues: %f % f %f\n', eigenvalues(1), eigenvalues(2),
    eigenvalues(3));

    checkeq1 = subs(eq1, p4, i);
    checkeq1 = subs(checkeq1, x1, x11);
    checkeq1 = subs(checkeq1, x2, x21);
    checkeq1 = subs(checkeq1, x3, x31);
    checkeq1 = subs(checkeq1, p6, p61);
    fprintf(fres, 'System: %f, ', checkeq1);

    checkeq1 = subs(eq2, p4, i);
    checkeq1 = subs(checkeq1, x1, x11);
    checkeq1 = subs(checkeq1, x2, x21);
    checkeq1 = subs(checkeq1, x3, x31);
    checkeq1 = subs(checkeq1, p6, p61);
    fprintf(fres, '%f, ', checkeq1);

    checkeq1 = subs(eq3, p4, i);
    checkeq1 = subs(checkeq1, x1, x11);
    checkeq1 = subs(checkeq1, x2, x21);
    checkeq1 = subs(checkeq1, x3, x31);
    checkeq1 = subs(checkeq1, p6, p61);
    fprintf(fres, ', %f\n', checkeq1);

    detcheck1 = subs(detcheck, p4, i);
    detcheck1 = subs(detcheck1, x1, x11);
    detcheck1 = subs(detcheck1, x2, x21);
    detcheck1 = subs(detcheck1, x3, x31);
    detcheck1 = subs(detcheck1, p6, p61);
    fprintf(fres, 'detcheck: %f\n\n', detcheck1);

    check2 = subs(res, p4, i);
    check2 = subs(check2, x1, x12);
    check2 = subs(check2, x2, x22);
    check2 = subs(check2, x3, x32);
    check2 = subs(check2, p6, p62);
    check2tmp = det(check2);
    fprintf(fres, '2:\n det = %f \n', check2tmp);
    eigenvalues = eig(check2);
    fprintf(fres, 'eigenvalues: %f % f %f\n', eigenvalues(1), eigenvalues(2),
    eigenvalues(3));

    checkeq2 = subs(eq1, p4, i);
    checkeq2 = subs(checkeq2, x1, x12);
```

```
    checkeq2 = subs(checkeq2, x2, x22);
    checkeq2 = subs(checkeq2, x3, x32);
    checkeq2 = subs(checkeq2, p6, p62);
    fprintf(fres, 'System: %f, ', checkeq2);

    checkeq2 = subs(eq2, p4, i);
    checkeq2 = subs(checkeq2, x1, x12);
    checkeq2 = subs(checkeq2, x2, x22);
    checkeq2 = subs(checkeq2, x3, x32);
    checkeq2 = subs(checkeq2, p6, p62);
    fprintf(fres, '%f, ', checkeq2);

    checkeq2 = subs(eq3, p4, i);
    checkeq2 = subs(checkeq2, x1, x12);
    checkeq2 = subs(checkeq2, x2, x22);
    checkeq2 = subs(checkeq2, x3, x32);
    checkeq2 = subs(checkeq2, p6, p62);
    fprintf(fres, '%f \n', checkeq2);

    detcheck2 = subs(detcheck, p4, i);
    detcheck2 = subs(detcheck2, x1, x12);
    detcheck2 = subs(detcheck2, x2, x22);
    detcheck2 = subs(detcheck2, x3, x32);
    detcheck2 = subs(detcheck2, p6, p62);
    fprintf(fres, 'detcheck: %f\n\n', detcheck2);



end


fclose(fid);
fclose(fres);
```