Thrust allocation in dynamic positioning system based on particle swarm optimization algorithm

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***Abstract*—This paper is designed to optimize the process and the results of thrust allocation to reach the purpose of reducing the error, energy consumption and equipment wear. Based on the ship model CyberShipII, a constrained nonlinear mathematical optimization model of thrust allocation was carried out, and the particle swarm optimization (PSO) algorithm was used in order to achieve a better result. Combining with the simulation data and curves, it can be seen that using particle swarm optimization algorithm for thrust allocation can achieve less energy consumption, and the results can meet the requirements of thrust allocation. In addition, it verifies the impacts of the maximum of evolution generation and population size of the particle swarm optimization on the optimization results. Finally, it came to a conclusion that using particle swarm optimization to optimize the thrust allocation problem can accurately and quickly complete the assigned tasks, as well as achieve less energy consumption.**

Keywords- dynamic positioning; thrust allocation; PSO; penalty function

I. Introduction

Dynamic positioning(DP) system is a closed-loop control system. Thruster system involves all components and systems necessary to supply the DP system with thrust force and direction. To improve the positioning accuracy and ability of dynamic positioning system, as well as to reduce energy consumption and propeller wear, the study of thrust allocation is necessary. The instruction from the controller of thrust allocation unit is distributed to each propeller in the form of speed and angle, by which means the required thrust and torque is obtained to control position and heading of the ship. The DP thruster system has many different combinations of longitudinal force, lateral force and torque, which is often a redundant system. Therefore, the thrust allocation problem needed to be solved is to find a combination of the most efficient and the lowest power consumption in the combinations of a plurality of thrust and angle. Using an efficient optimization algorithm can not only effectively reduce fuel consumption, improve energy saving and emission reduction and educe the positioning error, but also can reduce equipment wear, increase the service life of related equipment, which has certain practical significance[1-3]. This paper takes the ship model CyberShipII of the GNC laboratory, which is in Norwegian University Science & Technology (NUST), as the object for research[4].The research is mainly about the optimization problem of thrust allocation based on particle swarm algorithm, thus the problem of designing controller and giving expected generalized thrust is not discussed here.

II. Mathematical model of thrust allocation problem

A. *Thrust allocation mathematical model ofCyberShipII*

In order to study thrust allocation of the ship, the establishment of thruster allocation model must be considered into the mathematical modeling of ship's motion. CyberShipII is equipped with a small RPM controllable channel propeller with double paddles in the bow and two RPM controllable main propellers equipped with rudders in the stern. Motion parallel coordinates fixed on ship is selected as the coordinate system for mathematical modeling[5], the coordinates and layout of propeller can be seen in Fig.1 and Fig.2. Propeller thrust distribution and feasible region of CyberShipII can be seen from Fig.3.

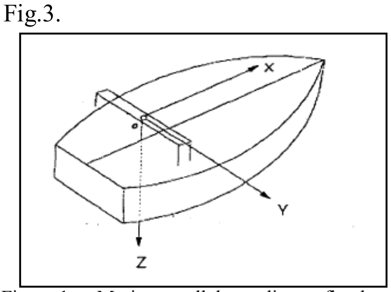

Figure 1. Motion parallel coordinates fixed on ship

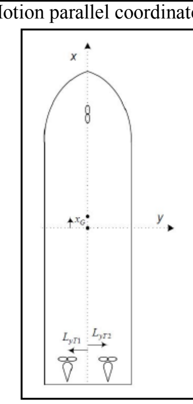

Figure 2. The layout of propellers

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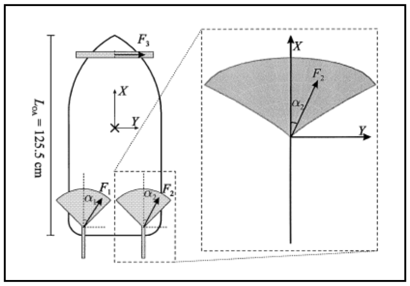

Figure 3. Thrust distribution and feasible region of CyberShipII

Thrust of fixed pitch propeller is proportional to square of shaft velocity. The propeller and rudder model of CyberShipII in low speed can be divided into two parts: the first part is the thrust of the propeller (rudder angle $\delta_i = 0, i = 1,2$).

$$T_i = \begin{cases} K_{iTp}\omega_i^2 & \omega_i \geq 0 \\ K_{iTn}|\omega_i|\omega_i & \omega_i \leq 0 \end{cases} \quad i = \{1,2,3\} \tag{1}$$

The second part is the lift force and resistance generated by the propeller rudder.

$$L_i = \begin{cases} T_i(1+K_{iLn}\omega_i)(K_{iL\delta 1}+K_{iL\delta 12}|\delta_i|)\,\delta_i & \omega_i \geq 0 \\ 0 \quad \omega_i \leq 0 \end{cases} \quad i = \{1,2\} \tag{2}$$

$$D_i = \begin{cases} T_i(1+K_{iLDn}\omega_i)(K_{iD\delta 1}|\delta_i|+K_{iL\delta 12}\delta_i^2) & \omega_i \geq 0 \\ 0 \quad \omega_i < 0 \end{cases} \quad i = \{1,2\} \tag{3}$$

For the three propellers and two rotary vanes, the longitudinal force and lateral force is as follows.

$$u_i = \begin{bmatrix} T_i - D_i & i = \{1,2\} \\ T_i & i = 3 \\ L_i & i = \{1,2\} \end{bmatrix} \tag{4}$$

The specific position of three thrusters in the coordinate (mapping to the body coordinates) are as follows.

$$r_{bt_1}^b = [-0.54 \quad -0.075]^T$$

$$r_{bt_2}^b = [-0.54 \quad 0.075]^T$$

$$r_{bt_3}^b = [1.14 \quad 0]^T$$

In the formulas above, $r_{bt_1}^b$ and $r_{bt_2}^b$ represent respectively for the coordinate of main thrusters located in the port and starboard of the ship, while $r_{bt_3}^b$ represents for that of the channel propeller with double paddles in the bow of ship. The parameters of propellers and rudders are given in table 1 and table 2.

TABLE I. THE PARAMETERS OF PROPELLERS

parameters	value/ Ns^2	parameters	value / Ns^2
K_{1Tp}, K_{2Tp}	$3.74 \cdot 10^{-3}$	K_{3Tp}	$1.84 \cdot 10^{-4}$
K_{1Tn}, K_{2Tn}	$5.05 \cdot 10^{-3}$	K_{3Tn}	$1.88 \cdot 10^{-4}$

TABLE II. THE PARAMETERS OF RUDDERS

parameters	value	unit
K_{1Ln}, K_{2Ln}	$2.10 \cdot 10^{-2}$	s
K_{1Dn}, K_{2Dn}	$9.64 \cdot 10^{-3}$	s
$K_{1L\delta 1}, K_{2L\delta 1}$	0.927	rad^{-1}
$K_{1L\delta 2}, K_{2L\delta 2}$	-0.557	rad^{-1}
$K_{1D\delta 1}, K_{2D\delta 1}$	0.079	rad^{-1}
$K_{1D\delta 2}, K_{2D\delta 2}$	0.615	rad^{-1}

According to the distribution of the propellers and rudders described above, the matrix of thrust applied on the hull is obtained:

$$\tau_{th} = Tu$$

$$\begin{bmatrix} \tau_X \\ \tau_Y \\ \tau_N \end{bmatrix} = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 \\ |L_{y1}| & -|L_{y2}| & |L_{x3}| & -|L_{x1}| & -|L_{x2}| \end{bmatrix} \cdot \begin{bmatrix} T_1(\omega_1,\delta_1) - D_1(\omega_1,\delta_1) \\ T_2(\omega_2,\delta_2) - D_2(\omega_2,\delta_2) \\ T_3(\omega_3) \\ L_1(\omega_1,\delta_1) \\ L_2(\omega_2,\delta_2) \end{bmatrix}$$

For the rudder in the stern, the maximum swing speed is 10 degree per minute. To make the swing speed of rudder is under the maximum value, i.e. $|\delta_z - \delta| \leq 10^\circ$, the maximum angle of rudder is $\delta_{\max} = 35^\circ$. The maximum speed of two string propeller mounted on the hull is $n_{1\max} = n_{2\max} = 20\ r/s$, while the maximum speed of groove propeller is $n_{3\max} = 35\ r/s$.

The specific configuration information and parameters of CyberShipII are substituted into the mathematical model above, the mathematical model of force distribution can be obtained.

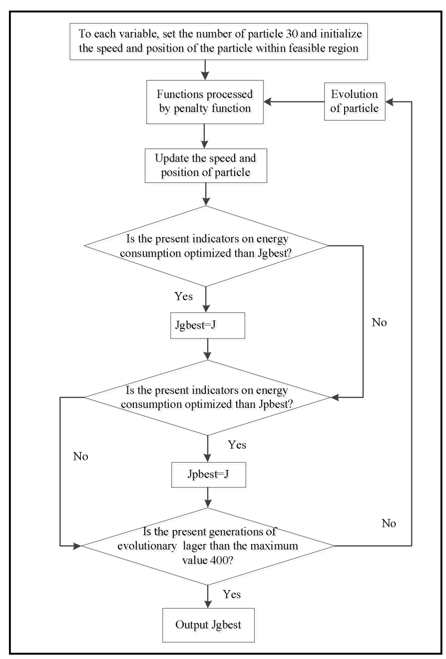

Figure 4. Process of thrust allocation with PSO algorithm

B. Thrust allocation optimization based on particle swarm algorithm

The basic principle and evolutionary model of particle swarm algorithm. Particle swarm algorithm is an effective mathematical tool for solving problems such as nonlinear continuous optimization, combinatorial optimization and mixed integer nonlinear optimization[6]. In the basic particle swarm optimization(PSO) algorithm, we can define the global best particle (position) or local best particle (position) to make up particle swarm algorithm with different social behaviors. The basic models are Gbest model (global best model), Lbest model (local best model) and w weight model [7].

For the expected longitudinal force, lateral force and rotation torque, the initial population of particles in PSO algorithm is obtained by random initialization of the optimization variables within the feasible region, at the same time, the particle search range is also restricted by the feasible region of optimization variables. In the process of optimization, each particle searches the optimal position (partial optimal solution $Pbest$), and affects the optimal position of population (global optimum $Gbest$), as well as being closer to the optimal position of population in the process of evolution, finally the optimal results can be obtained.

1) Process of thrust allocation optimization with PSO algorithm. In this paper, the objective function and the constraint conditions of the thrust allocation in CyberShipII can be described as follows.

$$J = \min[f_1 \quad f_2 \quad f_3]W\begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix}$$

$$\begin{aligned} s.t.: \tau_x &= f_1\cos\alpha_1 + f_2\cos\alpha_2 \\ \tau_y &= f_1\sin\alpha_1 + f_2\sin\alpha_2 + f_3 \\ \tau_n &= l_{1,x}f_1\sin\alpha_1 - l_{1,y}f_1\cos\alpha_1 + l_{2,x}f_2\sin\alpha_2 - l_{2,y}f_2\cos\alpha_2 + l_{3,x}f_3 \\ & f_{1\min} \le f_1 \le f_{1\max} \\ & f_{2\min} \le f_2 \le f_{2\max} \\ & f_{3\min} \le f_3 \le f_{3\max} \\ & \alpha_{1\min} \le \alpha_1 \le \alpha_{1\max} \\ & \alpha_{2\min} \le \alpha_2 \le \alpha_{2\max} \end{aligned}$$

In the formulas above, J represents for the energy consumption. f_1, f_2, f_3 are respective thrust force of the three propellers, α_1, α_2 are respectively angle of the two rudders. Coefficient matrix is as follows:

$$W = \begin{bmatrix} 1 & & \\ & \ddots & \\ & & 1 \end{bmatrix}$$

The idea of the penalty function is used to transform the constrained nonlinear problem into unconstrained nonlinear problem, then the actual optimization objectives of PSO can be obtained.

The effect of PSO algorithm is mainly decided by its parameters. After many experiments, the parameters are set as follows: population size is 30, the biggest iteration is 400, the learning factor is set as 2, while the weight coefficients is changed linearly from 0.9 to 0.4 in the previous 100 generation, then kept unchanged at 0.4

Process of thrust allocation with PSO algorithm can be seen from Fig 4.

III. SIMULATION TEST AND RESULTS

A. Comparison of energy consumption indicator between different allocation methods

Energy consumption is an important indicator in the thrust allocation process.

The rotating speed of three propellers($\omega_1, \omega_2, \omega_3$) and two rudder angle(δ_1, δ_2) are considered as the random input. Then we can get expected longitudinal force (τ_x), lateral force(τ_y) and gyration torque(τ_n). The energy consumption indicator J_{nor} can be calculated using the parameters obtained above. Take 15 sets of random data, the simulated results can be seen from table 3.

The longitudinal force, lateral force and gyration torque in table3 are considered as conditions for thrust allocation using PSO algorithm. In order to ensure the validity of the results, 15 groups of experiment are also carried out to obtain the results of thrust allocation and calculate the optimized consumption indicator at the same time. Each simulation is taken under the condition with population size 30, the maximum evolution generation is 400, learning factor is 2, the weight coefficient of the first 100 generation changes linearly from 0.9 to 0.4, followed by 0.4 kept unchanged. The simulation results can be seen in Table 4.

B. Test with typical conditions

Test Conditions a:

$$\tau_x = 10\ N,\ \tau_y = 10\ N,\ \tau_n = -5\ N \cdot M$$

Results of thrust allocations:

$$\omega_1 = 46.549317, \omega_2 = 42.772473, \omega_3 = 38.124062$$

Indicator of energy consumption:

$$J_{opt} = 68.24485\ J$$

The obtained parameters are taken into the mathematical model of thrust system of CyberShipII, the actual parameters calculated are as follows.

$$\tau_x = 9.999989\ N, \tau_y = 9.999999\ N, \tau_n = -5.269813\ N \cdot M$$

The error between actual value and the expected value is as follows.

$$\varepsilon_x = 0.00011\%, \varepsilon_y = 0.00001\%, \varepsilon_n = 5.96\%$$

The error is within range of the allowable error, as a result we can consider that the thrust allocation meets the requirement. Figure 5 shows that the algorithm has converged at about 70 generations of evolutionary and it found the optimal energy consumption indicator.

Test Conditions b:

$$\tau_x = -10\ N,\ \tau_y = -10\ N,\ \tau_n = 10\ N \cdot M$$

Results of thrust allocations:

$$\omega_1 = 70.760702, \omega_2 = -71.906048, \omega_3 = 68.095315$$

$$\delta_1 = -0.308782, \delta_2 = 0$$

Indicator of energy consumption is as follows.

$$J_{opt} = 968.4813\ J$$

The same method with above is used to get the actual longitudinal force, lateral force and gyration torques:

$$\tau_x = -9.999993\ N, \tau_y = -9.999967\ N, \tau_n = 9.649287\ N \cdot M$$

The error between actual value and the expected value:

$$\varepsilon_x = 0.00007\%, \varepsilon_y = 0.00033\%, \varepsilon_n = 3.51\%$$

The error is within the allowable error range, as a result we can consider that the thrust allocation meets the requirement. Fig. 6 shows that the algorithm has converged at about 100 generations of evolutionary and it found the optimal energy consumption indicator.

The PSO algorithm is used to optimize the objective function of two test conditions above and the optimized results can be seen respectively in Fig.5 and Fig6.

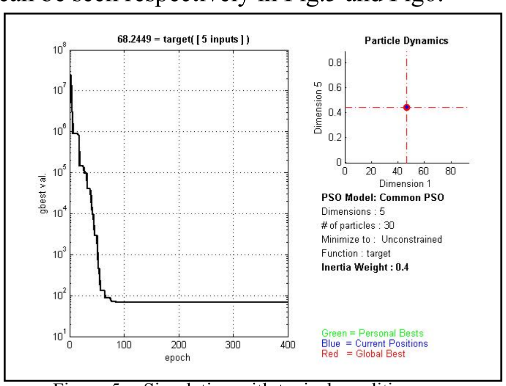

Figure 5. Simulation with typical condition a

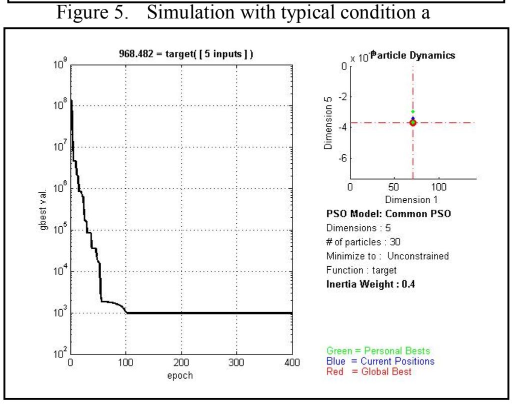

Figure 6. Simulation with typical condition b

According to the simulation and analysis with two typical conditions, it can come to a conclusion that the use of PSO algorithm for thrust allocation in dynamic positioning system can not only get optimization quickly and accurately, but also find better energy consumption indicator effectively.

C. The simulation test when the parameters of PSO algorithm are adjusted

PSO algorithm has some characteristics such as it can be achieved easily and the convergence speed is fast. At the same time, the final accuracy and speed of the optimization can be affected by the parameters. The main parameters considered here are the maximum evolution generation and population size. The expected conditions are the same as follows:

$$\tau_x = 10\ N, \tau_y = 10\ N, \tau_n = -5\ N \cdot M$$

1) The effect of maximum evolution generation. The other parameters of PSO: population size is 30, learning factor is 2, the weight coefficients of the previous 100 generation changes linearly from 0.9 to 0.4 and is kept unchanged at 0.4 later.

The simulation curve with maximum evolution generation 400 and 800 are shown in Fig. 7 and Fig. 8.

It can be seen that increase of the evolutionary generation will slow down the convergence speed and may miss the global optimal solution, according which we should select the appropriate maximum evolution generation.

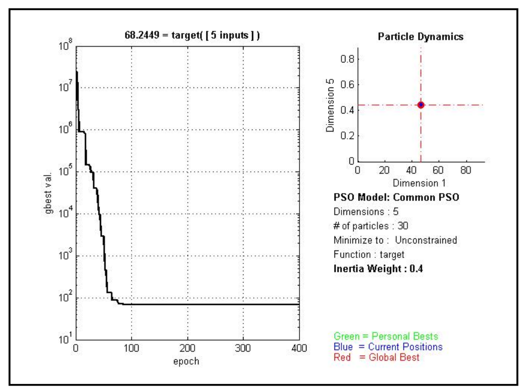

Figure 7. Simulation with maximum evolution generation 400

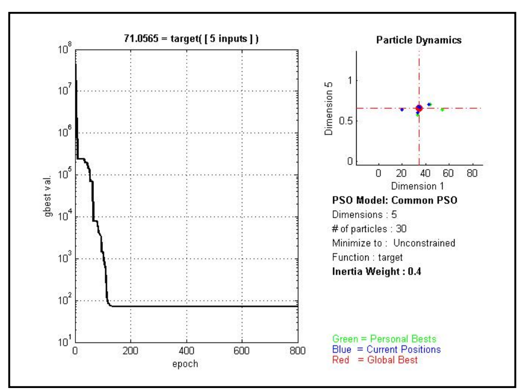

Figure 8. Simulation with maximum evolution generation 800

2) *The effect of the population size.* The other parameters of PSO: population size is 30, learning factor is 2, the weight coefficients of the previous 100 generation changes linearly from 0.9 to 0.4 and is kept unchanged at 0.4 later.

The simulation curve with population size 30 and 300 are respectively shown in Fig.9 and Fig.10.

It shows that when the population size is increased, the global optimal solution is essentially the same, but the convergence speed of the PSO algorithm will be seriously slow down, and after reaching the maximum evolution generation, there are still many local optimal solutions have not converged to the global optimal solution. Therefore, in order to ensure a better convergence speed, the population size should be selected appropriately.

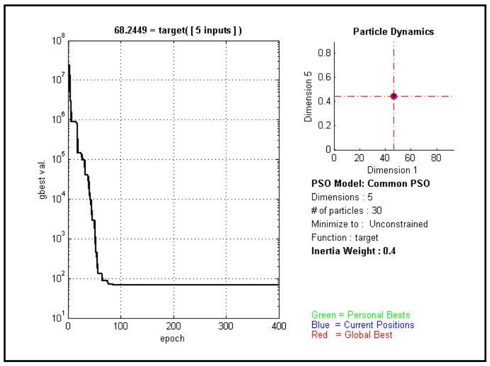

Figure 9. Simulation with population size 30

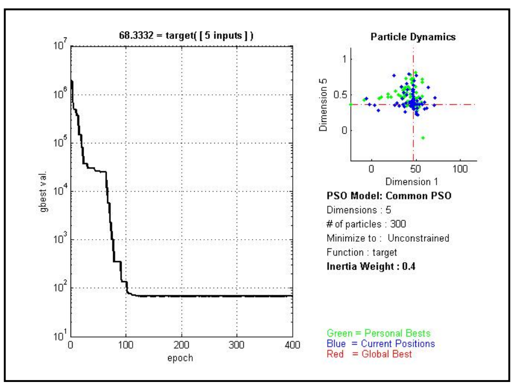

Figure 10. Simulation with population size 300

IV. CONCLUSION

The thrust allocation of dynamic positioning system will directly affect the effective functioning of the dynamic positioning system. Improving the quality of thrust allocation can not only finish the DP task effectively, but also can reduce error, reduce the consumption of fuel, avoid the attrition of equipment and save energy.

The ship model CyberShipII is used as the engineering background of thrust allocation optimization. Firstly, relative mathematical model is established according to the characteristics of CyberShipII. Secondly, the PSO algorithm is applied to solve the thrust allocation optimization problem of dynamic positioning system, and the tests of algorithm under typical conditions are carried out. Then, effects of different parameters in PSO algorithm are analyzed. The results obtained finally come to a conclusion that the thrust allocation of dynamic positioning system based on particle swarm optimization algorithm in this paper is feasible and effective.

ACKNOWLEDGMENT

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TABLE III. SIMULATED RESULTS WITH NORMAL ALGORITHM FOR THRUST ALLOCATION

Number	Expected value			Parameters of thrusters					
	Longitudinal force	***Lateral force***	***Rotation torque***	***Thrust of port propeller***	***Thrust of starboard propeller***	***Thrust of chanel propeller***	***Degree of Port rudder***	***Degree of starboard rudder***	***Energy consumation***
1	-20.89	-0.59	-0.29	36.54	-70.60	-123.55	0.3549	-0.6857	1087
2	-137.52	-7.45	-4.00	-119.52	-113.78	-199.12	-1.1610	-1.1052	54049
3	6.00	5.52	-2.33	4.97	44.93	78.63	0.0482	0.4364	44
4	14.13	18.15	-8.62	63.37	45.04	78.82	0.6156	0.4375	145
5	-20.28	63.84	-25.69	46.11	109.19	191.09	0.4479	1.0607	3016
6	-4.79	-0.49	0.07	-9.61	-29.26	-51.21	-0.0933	-0.2843	21
7	7.22	20.56	-10.72	74.96	4.88	8.54	0.7281	0.0474	91
8	-8.84	76.24	-39.25	101.54	83.14	145.49	0.9863	0.8076	611
9	-69.47	-7.87	1.68	-9.38	-116.92	-204.60	-0.0911	-1.1356	26877
10	-57.51	-2.67	-0.46	45.57	-112.17	-196.30	0.4427	-1.0896	18940
11	2.72	0.92	-0.29	27.01	7.46	13.06	0.2623	0.0725	7
12	6.59	5.06	-2.07	17.08	42.99	75.24	0.1659	0.4176	39
13	-97.77	-8.81	0.32	-63.77	-123.67	-216.42	-0.6194	-1.2012	46426
14	-13.11	41.40	-23.58	98.41	-29.29	-51.25	0.9559	-0.2845	252
15	-114.48	-6.82	-2.78	-104.07	-108.81	-190.42	-1.0109	-1.0569	25444

TABLE IV. SIMULATED RESULTS WITH PSO ALGORITHM FOR THRUST ALLOCATION

Number	Expected value			Parameters of thrusters					
	Longitudinal force	***Lateral force***	***Rotation torque***	***Thrust of port propeller***	***Thrust of starboard propeller***	***Thrust of chanel propeller***	***Degree of Port rudder***	***Degree of starboard rudder***	***Energy consumation***
1	-20.89	-0.59	-0.29	-39.54	-50.72	-56.01	0.0001	0.0002	232
2	-137.52	-7.45	-4.00	-106.93	-125.60	-175.08	0.0000	0.0000	9714
3	6.00	5.52	-2.33	4.89	46.03	59.34	-0.3002	0.4736	37
4	14.13	18.15	-8.62	9.27	74.17	84.41	-0.4957	0.4951	250
5	-20.28	63.84	-25.69	125.57	-109.24	63.96	0.4267	0.0000	2566
6	-4.79	-0.49	0.07	9.23	-31.41	-42.96	-0.7038	-0.0017	25
7	7.22	20.56	-10.72	0.97	74.26	54.65	-0.0925	0.7233	93
8	-8.84	76.24	-39.25	-49.73	120.97	100.63	-0.0055	0.7753	186
9	-69.47	-7.87	1.68	52.88	-125.57	-171.64	-0.1230	-0.0004	6476
10	-57.51	-2.67	-0.46	-125.37	77.67	135.68	-0.0009	-0.1184	6795
11	2.72	0.92	-0.29	12.86	25.24	32.30	-0.2049	0.3131	5
12	6.59	5.06	-2.07	47.56	-3.92	22.50	0.4259	-0.1299	21
13	-97.77	-8.81	0.32	-59.50	-125.60	-169.73	0.0000	0.0000	6957
14	-13.11	41.40	-23.58	94.70	45.07	30.53	1.0652	0.7178	231
15	-114.48	-6.82	-2.78	-82.95	-125.60	-176.50	0.0000	0.0000	7588