Multi-objective Optimization of Genetic Algorithm based on the NSGA -II Butterfly Valve

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Abstract

Based on fluid-structure interaction calculation, the curves of flow characteristics and flow resistance characteristics are obtained, and the structural strength of the valve at the opening degree of 0 is analyzed. The curve of flow characteristics is equal percentage, and the flow resistance coefficient decreases exponentially with the increase of opening degree. Maximum stress and maximum displacement of the butterfly valve at the opening degree of 0 meet the structural strength requirements. Meanwhile, the multi-optimization result for valve mass, maximum stress and maximum displacement is good. The valve mass decreases 0.61%, the maximum stress and maximum displacement at the opening degree of 0 respectively decreases 6.78% and 2.80%. At various opening degrees, the flow coefficient increases 5.41% at most, the flow resistance coefficient decreases 10.06% at most.

Keywords

Tri-eccentric butterfly valve; NSGA-II; Fluid-structure interaction; Multi-objective optimization.

1. INTRODUCTION

Valves are used to control the flow of the medium in the fluid system. They have the functions of regulating, turning off and checking. They are widely used in various fields of the national economy. With the need of social development and the increase of market demand, the valve industry in China has been developing rapidly in recent years, but there is still a certain gap compared with foreign advanced products.

Butterfly valve is a typical high performance regulating valve. In order to improve its design and manufacturing level, many scholars at home and abroad optimize the flow performance and structure of butterfly valve through numerical simulation analysis. In the field of structure, Sergio Corbera et al. proposed the multi-objective optimization design of butterfly valve structure based on genetic algorithm [1]. In China, Cui Baoling et al. compared and analyzed two kinds of butterfly plate structures, comb tooth type and wedge type, and studied the influence of butterfly plate shape on cavitation coefficient and flow resistance coefficient [2]. Liu Yangyang analyzed the stress condition and dangerous parts of butterfly valve, and improved the thickness and distribution of butterfly plate and floor plate [3]. In the field of fluid, Song Xueguan and Farid Vakili Tahami et al. used CFX software to simulate the flow field of butterfly valves, analyzed the relationship between the flow field characteristics of butterfly valves and the opening degree, and verified the accuracy of numerical simulation results. However, there may be a big difference between the simulated value and the measured value at a small opening degree [4-5]. In China, Liu Jian, Guan Honger, Jiang Lin et al. used CFX, Fluent and other software to simulate the steady and transient flow field of butterfly valve, get the distribution diagram of streamline, velocity and pressure, and analyze the flow field characteristics [6-8].

Based on the model of DN800 (D = 732 mm) triple eccentric butterfly valve as the research object, analyzes its structure and flow field characteristics, and the butterfly valve under normal working state of the most dangerous working conditions, based on genetic algorithm, the NSGA -II Workbench16.0 using ANSYS software to multi-objective optimization, provide theoretical basis for improving the butterfly valve performance.

2. THREE ECCENTRIC BUTTERFLY VALVE STRUCTURE CHARACTERISTICS

Butterfly valve is mainly composed of valve body, valve seat, valve shaft and valve plate, from the middle line, single eccentric, double eccentric, to the more advanced three eccentric butterfly valve, butterfly valve structure is gradually optimized and improved. The structural characteristics of three eccentric butterfly valve are shown in three eccentric centers, namely, the axial eccentric α and radial eccentric β between the center of the butterfly plate and the center of the valve seat, the center of the valve body, and the Angle eccentric θ [3] between the axis of the butterfly plate cone and the center line of the valve body, as shown in Figure 1. Three eccentric butterfly valve has obvious advantages in structure, its sealing form evolved from line contact to surface contact, reduce the leakage of butterfly valve, improve the high temperature and high pressure resistance of butterfly valve. However, because of its complex structure and manufacturing difficulty, the design and manufacturing of domestic three eccentric butterfly valve still face great challenges.

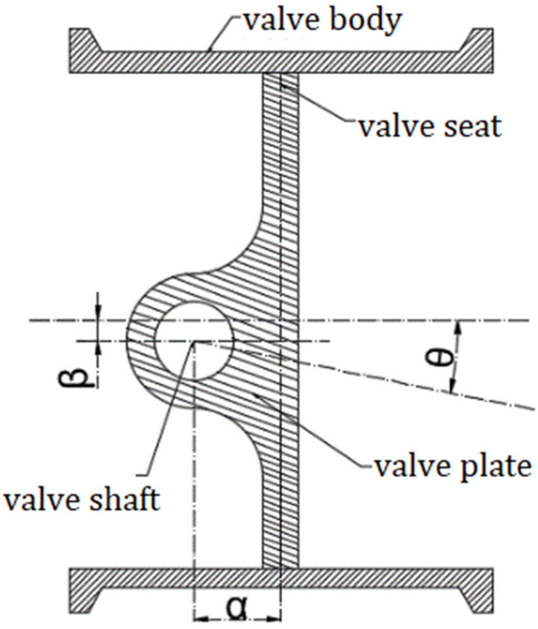


Figure 1. Three eccentric butterfly valve structure diagram

3. SIMULATION SUPPORT THEORY

3.1. Fluid-structure Coupling Analysis Theory

There is no single field problem in nature. All physical phenomena are coupled by two or more physical fields in electromagnetic field, displacement field, temperature field and flow field. The butterfly valve is always in the flow field in practical application, and the butterfly plate will inevitably deform under the action of Fluid, which will affect the flow of Fluid. Therefore, the butterfly plate and its flow field are analyzed by Fluid Structure Interaction (FSI). Fluid-structure coupling can be divided into unidirectional and bidirectional. Since the analysis of two-way fluid-structure coupling takes a long time, and the butterfly plate only needs to consider its static structural performance, this paper conducts unidirectional fluid-structure coupling analysis on butterfly valve. The fluid-structure coupling satisfies the basic conservation law, that is, on the fluid-structure coupling surface, the stress τ, displacement D, temperature T, heat flow Q and other variables correspond to the same or remain unchanged [9].

$$\begin{gathered}\tau_f \cdot n_f = \tau_s \cdot n_s \\ \mathrm{d}_f = \mathrm{d}_s \\ \mathrm{T}_f = \mathrm{T}_s \\ \mathrm{q}_f = \mathrm{q}_s\end{gathered} \tag{1}$$

3.2. Multi-objective Optimization Theory

Simultaneous optimization of multiple objectives is a multi-objective optimization problem, and the optimization of practical engineering problems mostly belongs to multi-objective optimization. Due to the conflict between targets, multiple targets often cannot achieve the optimal at the same time, and the optimization of one target may cause the deterioration of other targets. Therefore, the multi-objective optimization solution is a solution set, called the Pareto optimal solution set, and the corresponding image of objective function is called the Pareto frontier. Designers need to consider trade-offs when processing the optimization results.

In this paper, using the second generation of poor Sorting Genetic Algorithm (Non - dominated Sorting based Algorithm II, the NSGA - II) optimization. The NSGA - Ii algorithm is the improved version of NSGA and explore the performance and Pareto ability enhancement. In the process of calculation, based on user-defined, first of all have a certain number of individual parent population, in which random selection crossover and mutation have a certain number of individuals in subgroups, the two groups merge sort, by comparing the crowding factor to choose individual the formation of new species, repeat the above steps, until meet the termination conditions.

4. FLUID-STRUCTURE COUPLING ANALYSIS

4.1. Geometric Modeling

Based on the butterfly valve model given by the manufacturer, as shown in Figure. 2, the flow field calculation domain was established by appropriately simplifying the model details. In order to avoid vortices at the outlet, the length of the pipe before and after the valve is set to be 5D and 10D respectively to ensure the length of the stable section before and after the valve. The pipeline model is imported into ANSYS Workbench and passed to Fluid Flow (CFX) and Static Structure modules. Boolean operation was carried out on the pipeline and butterfly valve to control the part of butterfly valve that was irrelevant to the calculation of flow field. Three entities, the upstream pipeline (Body1), the front and rear of the butterfly valve (Body2) and the downstream pipeline (Body3), were obtained through slits, which were merged into a part to form a fluid calculation domain, as shown in Figure 3. In the modeling phase, the fluid-structure coupling interface is set up, which is customized as FSIfluid and FSIsolid in this paper, as shown in Figure 4.

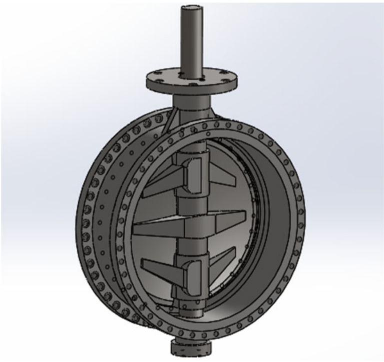


Figure 2. Isoaxometric drawing of butterfly valve structure

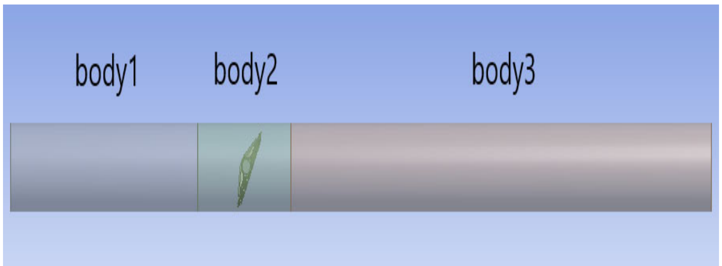


Figure 3. fluid calculation domain

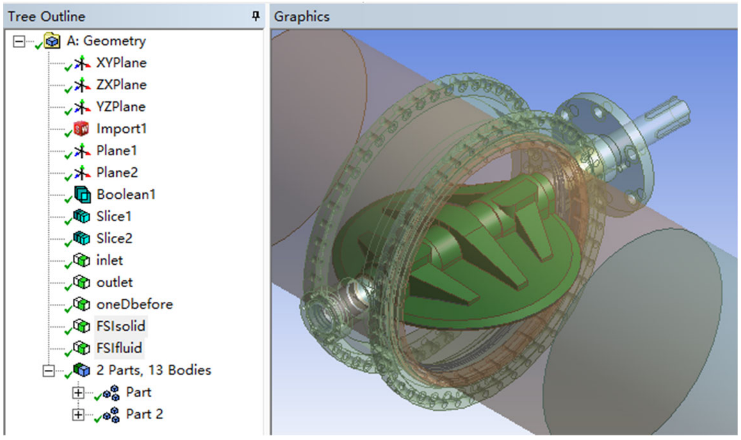


Figure 4. Fluid-structure coupling interface

4.2. The Flow Field Calculation

In the Fluid Flow (CFX) module, the Flow field calculation of butterfly valve with different opening degrees was carried out to suppress all solid parts. The upstream and downstream pipelines are divided into a hexahedral grid with a size of 40mm, the front and rear of the butterfly valve are divided into a tetrahedral grid with a size of 20mm, and the boundary layer thickness of the flow field is set as 7mm, as shown in Figure. 5. The fluid medium is 18°C seawater with a density of 1.025g/cm3 and a kinematic viscosity of 8.89E-4 kg/ms. The inlet flow rate was set at 2m/s, the outlet boundary condition was 0Pa, and the working pressure was 2MPa. All the walls (fluid boundary and the contact surface between fluid and butterfly plate) were adiabatic, non-slip and smooth. The standard k-ε turbulence model was selected, and the second order upwind scheme based on finite volume method and SIMPLE algorithm were used to solve the discrete equations. The convergence residual control of continuity equation and N-S equation is 10-6, and the time step and time scale are 150 steps and 2s, respectively.

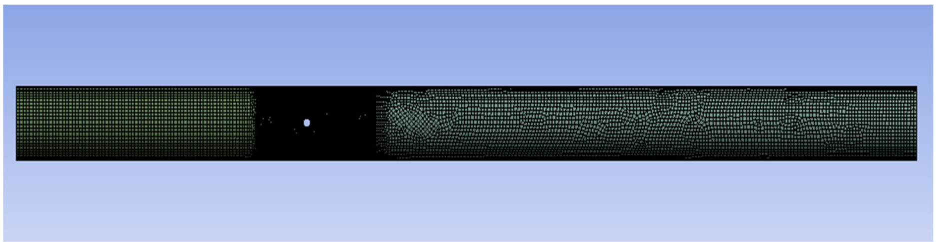


Figure 5. Flow field meshing

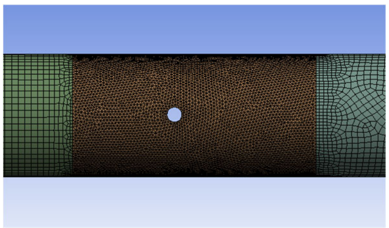


Figure 6. Flow field meshing

4.3. Structural Calculation

Butterfly plate Structure analysis is carried out in the Static Structure module to suppress the fluid domain and add materials for solid parts. The specific material parameters are listed in Table 1. As the butterfly plate is the key analysis object, it is divided into a tetrahedral grid with a size of 10mm, while other solid parts are divided into a hexahedral grid with a size of 20mm, as shown in Figure. 6. The calculation result of fluid Insert Pressure is that the force of fluid acting on the butterfly plate is the butterfly plate load. Frictional contact is set between the sealing ring, butterfly plate and valve seat, and the contact formula is Pure Penalty, with friction coefficient of 0.1 and normal stiffness of 0.01. Bonded contact is set as the rest. The boundary condition is set as the full displacement constraint (Fixed Support) of the flange faces at both ends of the valve body, as shown in Figure. 7. Finally, the stress and displacement distribution nephogram and deformation diagram of butterfly plate are obtained by solving.

Table 1. Material parameters

	Mass density (kg/m3)	Young's modulus	Poisson's ratio	The yield strength (MPa)
The casting of the carbon steel (Disc, valve body)	7800	2.00E+11	0.32	248.17
Alloy steel (Stem, locating sleeve)	7700	2.10E+11	0.28	620.42
Forged stainless steel (Seat, pressure ring, triple open ring)	8000	2.00E+11	0.26	206.81

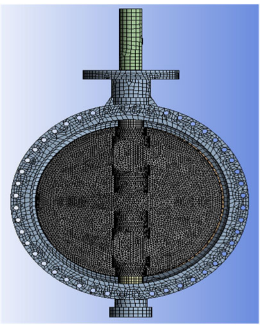


Figure 7. Solid parts meshing

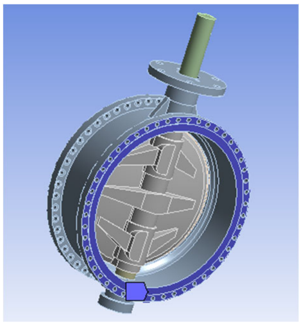


Figure 8. The boundary conditions

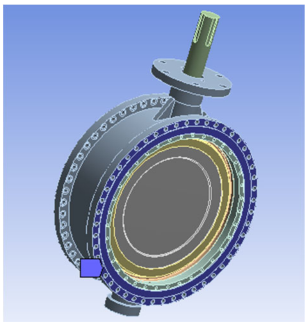


Figure 9. The boundary conditions

4.4. The Structural Strength

When the opening is 0°, the stress of the fluid acting on the butterfly plate surface is shown in Figure. 10, with the maximum stress of about 1.4758MPa. The stress distribution, displacement distribution and deformation of the butterfly plate are shown in Figure. 11. The stress distribution is basically symmetrical, with the maximum stress of 179.63MPa occurring at the center of the valve shaft surface. The maximum displacement was about 0.7402mm and occurred at the lower edge of the butterfly plate. It is known that the yield strength of the cast carbon steel is about 248MPa, so the maximum stress of the butterfly plate is less than the yield strength of the material. According to the valve design manual, the maximum deformation of the disc should be less than 1.25 times the thickness of the disc [10]. As the disc thickness is known to be 84.5mm, then 1.25×84.5mm=105.625mm>0.7402mm. Obviously, the maximum displacement of the disc is within the permitted range.

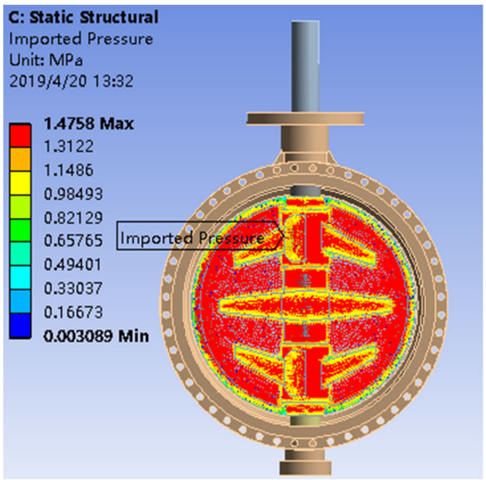


Figure 10. Fluid zone stress acting on disc surface

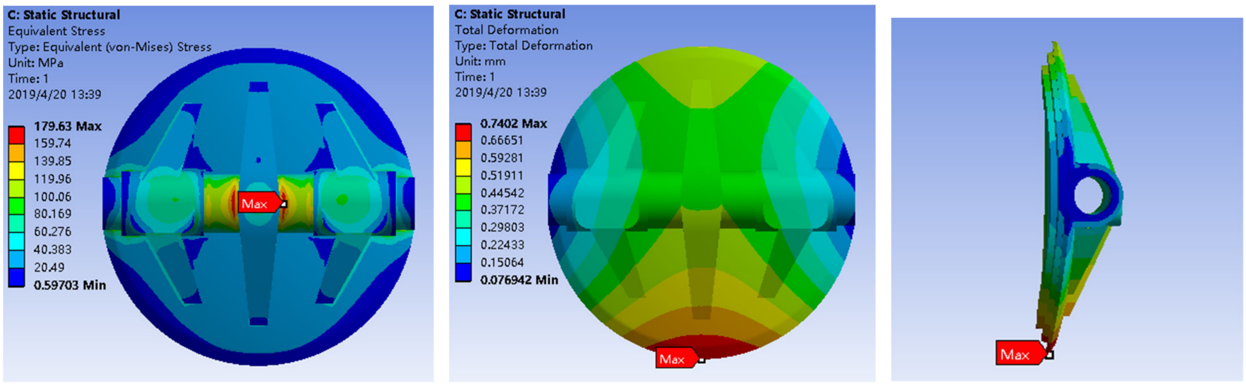


Figure 11. Fluid zone stress acting on disc surface

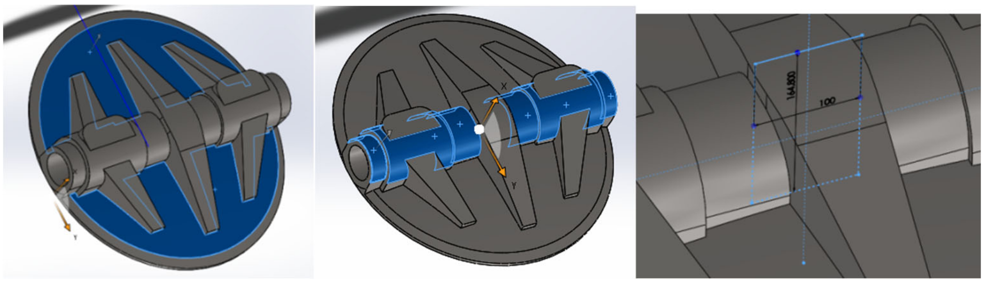
5. MULTIO-BJECTIVE OPTIMIZATION

5.1. Optimized Design Variable

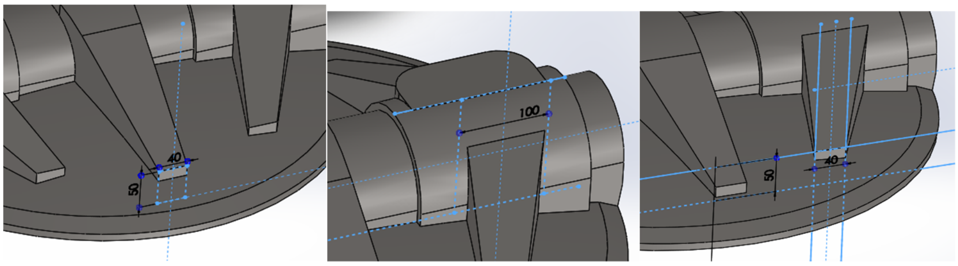
Considering the structure and shape of the butterfly plate comprehensively, the following 11 variables were taken as the global optimization parameters, which basically included all the variable parameters of the butterfly plate. The variable is set as continuous variable, and its lower limit and upper limit are specified. The specific values are listed in Table 4, and the specific positions are shown in Figure 12.

Table 2. Optimized design variable

The variable name	The initial value (mm)	The lower limit (mm)	The Ceiling Limit (mm)
radius1	1647.953	1500	1800
radius2	67	60	72
radius3	75	72	78
radius4	61	55	65
width1	100	90	110
height1	164.8	158	170
width2	40	35	45
height2	50	40	55
width3	100	90	110
width4	40	35	45
height4	50	40	55



(a) radius1 (b) radius2-4 (c) width1, height1



(d) width2, height2 (e) width3 (f) width4, height4

Figure 12. The specific position of design variables in the butterfly plate structure

5.2. Constraint Condition and Objective Function

The constraint condition is that the maximum stress of the butterfly plate does not exceed the yield strength of the material. The objective function is the minimum stress (σ_max), the minimum displacement (ω_max) and the minimum Mass (Mass) of butterfly valve. The following multi-objective optimization mathematical model is established:

$$\begin{gathered}\text{Find } Candidate = (P1, P2, P3, \dots, P9, P10, P11) \\ \min F(\sigma_{max},\ \omega_{max},\ Mass) \\ \text{s.t.}\, \sigma_{max} \le 248.17\text{Mpa}\end{gathered} \tag{2}$$

Set the Objective Importance and Constraint Importance of the Objective functions σ_max and Mass as Higher, and the Importance of ω_max as Default.

5.3. Sensitivity Analysis

Based on Direct Optimization module, the sensitivity between the design variable and the Optimization target, that is, the influence degree, is analyzed to determine whether the selection of the design variable is reasonable. As shown in Fig. 13, Radius4 has a high sensitivity to MASS during the optimization process. Width2 is sensitive to ω_max. Radius4 has a high sensitivity to σ_max. The other parameters are less sensitive to the objective function. Therefore, the optimization design of butterfly plate structure can focus on the improvement of valve shaft outer wall radius and center stiffener.

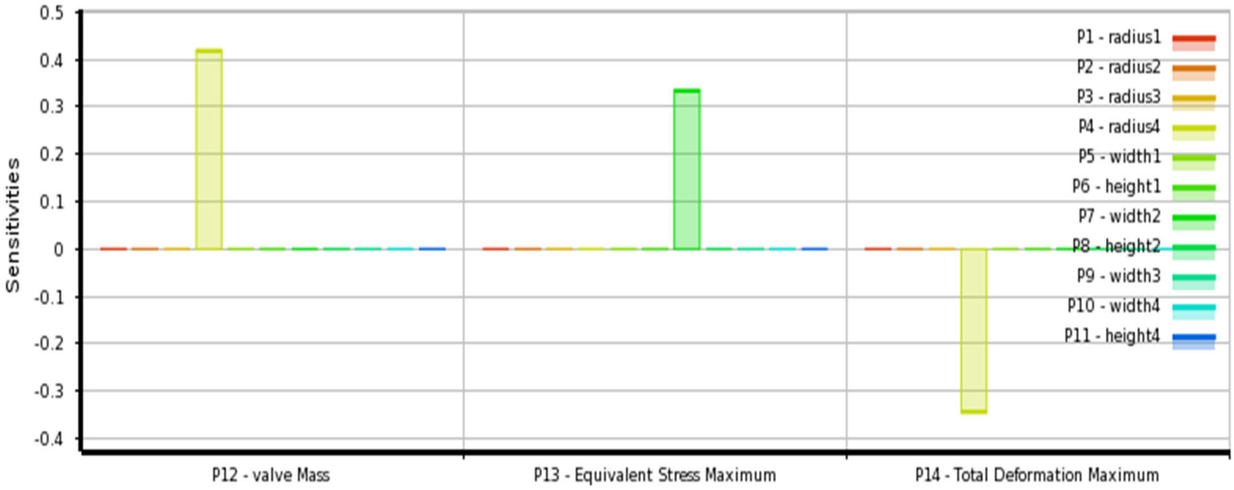


Figure 13. Fluid zone stress acting on disc surface

5.4. The Optimization Results

The NSGA - II computing, genetic algorithm to obtain the Pareto front, as shown in figure 14. After 12 iterations and calculation of convergence, 647 groups of design points were obtained. Finally, three groups of optimal values were given, which are listed in Table 5. After comprehensive comparison of the importance of each objective function, this paper chooses Candidate1 as the optimization result and conducts fluid-structure coupling analysis on the optimized butterfly plate structure. The calculation results are shown in Table 6 and Figure 15. Under the condition that all parameters remain unchanged, the stress and displacement of the optimized butterfly plate structure are basically the same as before. The maximum stress decreases from 179.63MPa to 167.46MPa, the maximum displacement decreases from 0.7402mm to 0.71946mm, and the weight of the butterfly plate decreases from 231.37kg to 229.96kg. The optimization rates of the three objective functions are 6.78%, 2.80% and 0.61%, respectively.

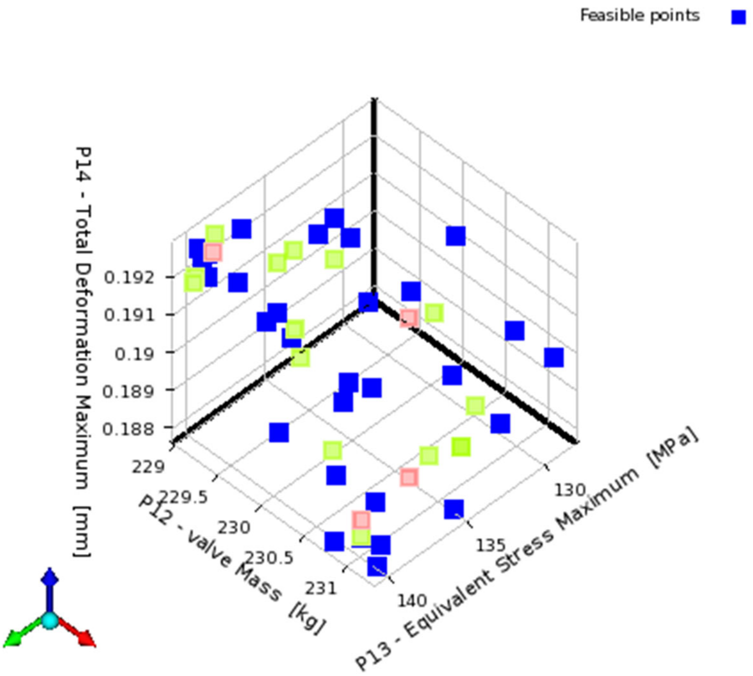


Figure 14. Pareto frontier

Table 3. The NSGA - II algorithm optimization value

The variable name	The initial value (mm)	Candidate1(mm)	Candidate2(mm)	Candidate3(mm)
radius1	1647.953	1651.6	1650.7	1638.5
radius2	67	68.527	67.947	68.414
radius3	75	72.455	73.118	73.142
radius4	61	56.779	60.685	56.769
width1	100	95.977	109.98	101.11
height1	164.8	167.83	169.11	167.82
width2	40	39.927	44.221	39.763
height2	50	54.872	51.597	49.882
width3	100	102.07	102.12	101.74
width4	40	44.633	43.57	44.344
height4	50	48.485	40.61	47.393

Table 4. The optimization results

The objective function	The initial value	The optimal value	To optimize the rate
σ_{max}(MPa)	179.63	167.46	6.78%
ω_{max}(mm)	0.7402	0.71946	2.80%
Mass(kg)	231.37	229.96	0.61%

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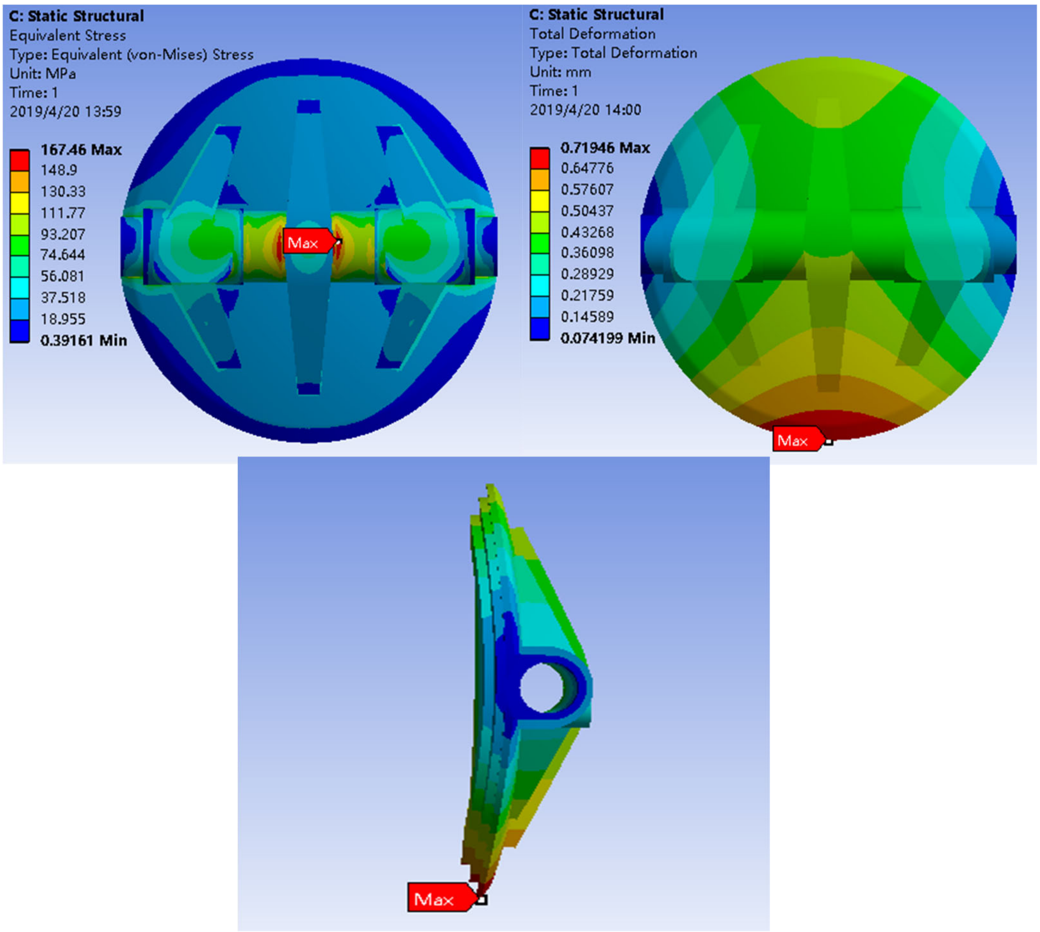

Figure 15. The optimized butterfly plate stress and displacement distribution nephogram and deformation diagram

6. CONCLUSION

Overview of DN800 triple eccentric butterfly valve is fluid-structure coupling analysis and based on the NSGA - II the multi-objective optimization of genetic algorithm, to butterfly plate quality, the maximum stress and maximum displacement as the target function, calculation and analysis before and after optimization of butterfly valve flow coefficient, flow resistance coefficient and butterfly plate quality, structural strength, good optimization results were obtained. The specific conclusions are as follows:

(1) The flow characteristic curve of butterfly valve shows an equal percentage characteristic; The flow resistance characteristic curve shows that the flow resistance coefficient decreases exponentially with the increase of the butterfly valve opening.

(2) Before optimization, the maximum stress and maximum displacement of the butterfly plate in the fully closed state are 179.63MPa and 0.7402mm, which meet the requirements of structural strength. The greater stress area of the disc is concentrated in the center of the disc, the valve shaft and the stiffeners on both sides. The larger displacement area is at the lower edge of the butterfly plate.

(3) based on genetic algorithm, the NSGA - II to butterfly plate the global variables as design optimization of multi-objective optimization is feasible, and the result is accurate. The mass of the butterfly plate is reduced by 0.61%, the maximum stress and maximum displacement of the butterfly plate are reduced by 6.78% and 2.80% respectively in the fully closed state. The maximum optimization rates of flow coefficient and flow resistance coefficient are 5.41% and 10.06% of those under full open condition, respectively. The variation of valve shaft wall

thickness and center stiffener size is sensitive to the optimization objective and should be paid more attention to in the actual design optimization process.

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