Multi-Objective Optimization of Efficiency and Pressure Fluctuation for Vertical Inline Pump

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Abstract. Vertical inline pump is a single-stage single-suction centrifugal pump. In order to save the installation space, there is a bent pipe before the impeller. In this paper, to achieve efficient and stable operation of the pump, a multi-objective optimization of efficiency and pressure fluctuation on the inlet pipe of vertical inline pump was proposed based on Latin Hypercube Sampling. The geometric shape of an inlet pipe is controlled by the mid curve and the shape of cross section. The fifth-order Bezier curve was adopted to fit the mid curve and a round cross section was set. Totally 7 design parameters of the inlet pipe were selected as design variables, and the pump efficiency and the pressure fluctuation amplitude at the tongue were set as the optimization objectives. 36 groups of sample points were obtained from Latin hypercube sampling (LHS). The results showed that at design flow rate, the efficiency increased from 77.60% to 79.33%. Comparing with prototype, the pressure fluctuation amplitudes of main frequency at two monitoring points were decreased by 0.89% and 9.15%. It was observed that the profile of inlet pipe has an obvious influence on the pump performance and unsteady flow characteristics. Therefore, the profile of inlet pipe will be the key component for the optimization of vertical inline pump, and this study can provide theoretical guidance for researching the hydraulic efficiency and unsteady pressure fluctuation.

1. Introduction

Vertical pipeline pump is an important form of centrifugal pumps with the characteristics of compact structure, small footprint, easy installation and maintenance. Therefore, it is usually applied in limited installation space, such as high-rise water supply and ship transportation[1]. In order to achieve the inlet and outlet pipe on the same line, elbow bent pipe was adopted as inlet structure of the pump. Compared with ordinary single-stage single-suction centrifugal pump, it results in the low pump efficiency and hydraulic losses. Therefore, the optimization design on inlet pipe of vertical inline pump needs to consider high performance, stability and service life. In recent years, research has been carried out on the hydraulic performance optimization of the pump and the effect of inlet pipe on inner flow[2-4].

At present, the research mainly focuses on the influence of geometric parameters on unsteady pressure fluctuation and analyzes it in the time and frequency domain. It is necessary to put forward the optimization method with the target of reducing pressure fluctuation. Choi[5] monitored the velocity field of outlet jet wake with hot-wire probes, and found that instability flow causes a periodic pressure fluctuation on the blade surface by interacting with the impeller blades near the trailing edges. Geng et al.[6] investigated the effects of three different blades on the full flow field characteristics of
centrifugal pumps through numerical simulation. Yuan [7] analyzed the internal flow conditions of centrifugal pumps through unsteady numerical simulation calculations, studied rotor-stator interaction effects between the impeller and the tongue, and performed time-frequency domain analysis on the pressure fluctuation at each monitoring point. Furthermore, Keller et al. [8], Zhang et al. [9] and Lu et al. [10] have successfully investigated the effects of blade wake vortices at different working conditions, different blade outlet angles and different clocking positions on unsteady pressure pulsation characteristics, respectively. Referring to research on hydraulic optimization methods, they are mainly based on steady calculations with optimization goals such as efficiency, head, and cavitation performance. This leads to the lack of optimization on unsteady characteristics. Zangeneh et al. [11] combined multi-objective genetic algorithm and three-dimensional reverse design method to conduct the optimization design of cavitation performance of centrifugal pumps and sweep angle of impeller inlet. An optimization process is proposed based on Kriging model and neighborhood cultivation genetic algorithm by Wang et al. [12] to seek the optimal solutions of head and efficiency. Zheng et al. [13] applied orthogonal experiment in multi-objective optimization design of axial flow pumps, taking head, efficiency, axial power and pressure pulsation as experiment evaluation indexes.

In order to improve hydraulic efficiency and decrease pressure fluctuation amplitude, a multi-objective optimization of vertical inline pump was proposed based on Latin hypercube sampling. Three-dimensional unsteady numerical simulation on different profiles of inlet pipe is carried out. 7 design variables of inlet pipe are utilized for optimization, and the optimization objectives are the pump efficiency and the pressure fluctuation amplitude at design condition. After that, the analysis is conducted on hydraulic efficiency and inner flow.

2. Calculation Model and Computational Grids

2.1. 3D Model

The model of vertical inline pump used in this study is shown in figure 1. In order to simplify the meshing process, the flow domain of vertical inline pump in the calculation was divided into 4 parts: inlet pipe, impeller, volute and delivery pipe. Table 1 lists the main design parameters of vertical inline pump. The specific speed \( n_s = 132.36 \) and the formula is shown in equation (1). To ensure the reliability of numerical simulation, the length of inlet and outlet pipes are set to 10 times pipe diameter.

\[
n_s = 3.65 \times \frac{n \times \sqrt[4]{Q_d}}{60 \times H^{1/4}}
\]  

(1)

Where \( n_s \) denotes the specific speed of the pump, \( n \) is the rotating speed of impeller, rpm, \( Q_d \) represents the volume flow rate of design point, \( m^3/h \), \( H \) stands for the pump head, m.

![Figure 1. Computational model.](image-url)
### Table 1. Main design parameters.

| Parameters               | Value   |
|--------------------------|---------|
| Flow rate, \( Q_n \) (m\(^3\)/h) | 50      |
| Total head, \( H \) (m)          | 20      |
| Rotational speed, \( n \) (rpm)   | 2910    |
| Specific speed, \( n_s \)          | 132.36  |
| Impeller inlet diameter, \( D_1 \) (mm) | 73      |
| Impeller outlet diameter, \( D_2 \) (mm) | 136     |
| Inlet width, \( b_1 \) (mm)        | 34.5    |
| Outlet width, \( b_2 \) (mm)       | 17.8    |
| Inlet vane angle, \( \beta_1 \) (deg) | 28.6    |
| Outlet vane angle, \( \beta_2 \) (deg) | 30.3    |
| Number of blades, \( z \)          | 6       |
| Suction pipe diameter, \( D_s \) (mm) | 80      |
| Delivery pipe diameter, \( D_d \) (mm) | 80      |

2.2. **Computational Grid**

High-quality grids can improve the speed and accuracy of iterative calculation in the numerical simulation. In this research, structured grids were generated by ANSYS ICEM CFD. To capture complex flow phenomena, the layer-adapted meshes were adopted in flow sensitive areas, including tongue and impeller leading edge regions. The detailed grids are shown in figure 2, where \( y^+ \) of the sensitive area was less than 10, and the maximum value of the flow domain is 80.

In order to ensure the calculation accuracy and speed, the grid sensitivity study of the model was carried out. According to the analysis result, when the nodes’ number of impeller is more than \( 0.85 \times 10^6 \), the head and efficiency of vertical inline pump tend to be stable. The grid quantity of different domains finally selected is shown in table 2.

### Table 2. Main design parameters.

| Domain        | Number of nodes |
|---------------|-----------------|
| Inlet pipe    | 1,361,122       |
| Impeller      | 933,510         |
| Volute        | 1,216,305       |
| Outlet pipe   | 779,544         |

![Figure 2. Computational grid.](image-url)
3. Numerical Methodology
For the purpose of capturing the unsteady flow characteristics in the vertical inline pump, this paper adopts the calculation software ANSYS CFX to combine the 3D Reynolds-averaged Navier-Stokes (RANS) equation with the SST (Shear Stress Transport) turbulence model to carry out numerical simulation of the computational model (see figure 1).

Specifically, the setup conditions for unsteady calculations are shown in table 3. The inlet and outlet boundary condition were total pressure inlet and mass flow rate outlet, independently. The timestep was 0.00017182s and each timestep corresponds to the impeller rotation of 3 degrees. Each rotating period is 120 timesteps. The total number of turns is 5 with a total of 600 timesteps per run. To keep boundary conditions close to the real conditions, the reference pressure was set as 101.325 kPa. All solid walls were considered as no slip, and the wall roughness was 25μm. The interface between rotor and stator was set as “Transient rotor stator”. In addition, the standard of convergence was residual of continuity and momentum equations with the value $1 \times 10^{-4}$.

Table 3. Numerical calculation setup.

| Setup item                          | Option                      |
|------------------------------------|-----------------------------|
| Analysis Type                      | Transient                   |
| Timesteps                          | $1.7182 \times 10^{-4}$ s   |
| Timesteps per run                  | 600                         |
| Inlet boundary condition           | Total pressure inlet, 1atm  |
| Outlet boundary condition          | Mass flow rate outlet       |
| Reference pressure                 | 1atm                        |
| Mass and momentum                  | No slip wall                |
| Wall roughness                     | 25μm                        |
| The interface between rotor and stator | Transient rotor stator     |
| Convergence precision              | $1 \times 10^{-4}$          |

4. Optimization Process

4.1. Optimization Variables
In this research, the profile of inlet pipe for vertical inline pump was set as the optimization object. As shown in figure 3 and figure 4, the geometric shape of an inlet pipe is controlled by the mid curve and the shape of cross section. The mid curve of inlet pipe was fit by a fifth-order Bezier curve. To reduce the design variables and calculated dimension, the shape of cross section was set as round, which means $D$ was equal to $L$ in figure 4.

![Figure 3. Mid curve.](image1)

![Figure 4. Cross section.](image2)
Totally, there are 6 points controlling the Bezier curve shown in figure 3. The positions of P0 and P5 control the relative positions of the sections A and F, respectively. Section A is the interface between vertical inline pump and inlet pipe, and section F is the interface between inlet pipe and impeller. According to the pump characteristics, the longitudinal position of section A was fixed and section F was a fixed section. It means the longitudinal coordinate of P0 and the position of P5 were all fixed. In order to obtain smooth streamline at the curve, the longitudinal coordinate of P1 should be equal to P0, and the horizontal coordinate of P4 should also be equal to P5. x and y represent the horizontal and longitudinal coordinates of control points, respectively. And the subscript is the number of control points.

In general, there were totally 7 design variables in the optimization design. They were \(x_0, x_1, x_2, y_2, x_3, y_3, y_4\). The boundaries of design variables are shown below.

### Table 4. Boundary values of design variable.

| Variables | \(x_0\) | \(x_1\) | \(x_2\) | \(y_2\) | \(x_3\) | \(y_3\) | \(y_4\) |
|-----------|---------|---------|---------|---------|---------|---------|---------|
| Upper bounds | -180 | -120 | -120 | -80 | -90 | -90 | -110 |
| Lower bounds | -350 | -160 | -160 | -160 | -120 | -160 | -220 |

4.2. Objective Functions

For the purpose of achieving the high efficiency and stabilization of vertical inline pump, this paper set the efficiency and the pressure fluctuation amplitude at design flow rate as objective functions. The mathematical definitions are shown as follow.

\[
\begin{align*}
\{ f_{1,OQ} > 78.5\% \\
\min A
\end{align*}
\]

(2)

Where \(f_{1,OQ}\) denotes the efficiency at design flow rate, and \(A\) is the pressure fluctuation amplitude at main frequency of the pump defined as the difference value between the maximum and minimum of pressure fluctuation over a period.

4.3. Optimization Procedure

In this research, the procedure for the optimization of pump efficiency and pressure fluctuation was shown in figure 5. To be specific, 36 groups of sample points were constructed by Latin hypercube sampling according to boundary conditions of variables. Then 36 different three-dimensional models of inlet pipe were created by CREO Parametric, which were in line with above sample data. To obtain the external characteristic values and flow feature, numerical analysis was achieved based on the ANSYS CFX. In this way, 36 groups of sample data and the corresponding objective function values were obtained. Then the original model and the optimized model selected from above samples were compared with the standard of maintaining the pump performance at a certain level and reducing the pressure fluctuation amplitude.

In order to integrate the above software and realize the automatic optimization process, all software used were controlled by MATLAB and BAT codes. Specifically, the modeling process of CREO Parametric were controlled by a trail tracking file to achieve parametric modeling capabilities. To integrate the pre-processing software Meshing and CFD solver, the ANSTS Workbench was adopted with a trail file in batch pattern, which achieved subsequent automatic meshing and numerical analysis.

4.4. Latin Hypercube Sampling

Latin Hypercube Sampling (LHS) is a kind of sampling methods with the great property of space filling and nonlinear filling\(^{[14]}\). Generally speaking, LHS includes three steps to generate a number of distributional vectors from the multidimensional area: (a) equally divide the range of each variable based on the number of samples. (b) randomly select one point from each interval. (c) obtain a sample matrix on the base of the values of the different variables above.
In order to reflect the design space to the great extent, 36 groups of design points were generated by LHS. The samples are shown in table 5.

![Optimization Procedure](image)

**Figure 5.** Optimization Procedure.

| Initial value | $x_0$   | $x_1$   | $x_2$   | $y_1$   | $x_3$   | $y_2$   | $x_4$   | $y_3$   | $y_4$   |
|---------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| 1             | -285.51 | -151.48 | -147.81 | -105.21 | -95.01  | -143.87 | -219.28 |
| 2             | -181.17 | 147.84  | -138.04 | -100.17 | -107.77 | -122.70 | -120.66 |
| 3             | -302.14 | -123.83 | 126.04  | -82.80  | -93.13  | -130.50 | -215.76 |
| 4             | -264.74 | -150.42 | -142.69 | -81.69  | -112.56 | -100.84 | -211.96 |
| 5             | -294.95 | -148.81 | -137.20 | -93.05  | -98.07  | -140.91 | -140.16 |
| 32            | -294.45 | -141.65 | -132.21 | -132.21 | -110.28 | -155.74 | -187.86 |
| 33            | -181.98 | -158.20 | -120.69 | -98.70  | -118.84 | -90.84  | -165.22 |
| 34            | -283.85 | -129.46 | -130.01 | -115.39 | -98.37  | -104.21 | -112.01 |
| 35            | -244.21 | -139.73 | -149.94 | -149.07 | -103.45 | -149.37 | -119.16 |
| 36            | -235.47 | -137.11 | -125.50 | -141.03 | -92.74  | -152.29 | -171.98 |

**Table 5.** Boundary values of design variable.

5. Results and Discussion

5.1. Experimental validation of numerical simulation
In order to verify the stability of the results for numerical simulation, the external characteristic experiment was carried out on the test bench. The test bench is an open-loop system. The uncertainty of head and efficiency were ±2%, and the measurement error of flow rate was less than 0.2%. The pressure sensor was adopted to measure the inlet and outlet pressures. The measuring ranges are 0-1.6 bar and 0-4 bar, respectively. The motor speed and the flow rate were controlled by the frequency conversion speeder and the throttle. Beside these, a number of external characteristic experiment were conducted on the vertical inline pump to ensure the reliability of the experimental results.

As following formulas, the experimental and computational results were all displayed with dimensionless parameters.

\[
\psi = \frac{2gH}{u_c^2} \tag{3}
\]

\[
\phi = \frac{Q}{\pi D b_2 u_c} \tag{4}
\]

As shown in figure 6, there was an agreement between the experimental and computational results. At the design condition, the relative errors of head and efficiency are independently 1.33% and 7.2%.

5.2. Comparison of hydraulic performances

As shown in table 6, the values of design parameters of original design and optimized design were clearly listed. The optimized model was selected based on pump efficiency greater than 78.5% and maximum pressure fluctuation amplitude reduction at monitoring points. To be specific, it shows that the increase of pump efficiency was 1.73%. However, the head of the pump rose from 19.81m to 20.12m. The deviation of head between original model and optimized model was 1.56%. On account of vertical inline pump mainly applied in high-rise water supply, this error of head is within acceptable limits compared with the improvement of efficiency. This will make for the efficient operation of the pump in practical applications. Therefore, the profile of inlet pipe has obvious influence on the hydraulic performances of the pump.

Table 6. Comparison of original design and optimized design of hydraulic performances.

| Name          | $x_0$ | $x_1$ | $x_2$ | $y_2$ | $x_3$ | $y_3$ | $y_4$ | $\eta$ | $H$   |
|---------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Original model| -200  | -159.70 | -128.70 | -74.66 | -45.73 | -75.38 | -69.57 | 77.60% | 19.81 |
| Optimized model| -264.74 | -150.42 | -142.69 | -81.69 | -112.56 | -100.84 | -211.96 | 79.33% | 20.12 |

5.3. Inner flow analysis
Figure 7 shows the velocity distribution on the mid plane of inlet pipe at the design flow rate. It was observed that the inlet pipe of optimized design becomes smoother compared with original design. After optimization, the second bend was farther from the outlet of inlet pipe. Therefore, after optimization, there was a longer distance line before the outlet, so that the outflow velocity distribution became more uniform. In the optimized model, the outflow direction of inlet pipe was almost vertical, while in the original model, the outflow direction was inclined to the right. At the same time, the low-speed area occupies less after optimization, and the flow mainly existed in the center part of the channel.

The velocity distribution of the outlet section at the design flow was shown in figure 8. It was obvious that after optimization, the velocity distribution on the outlet section was more uniform, and the velocity gradient on the outlet section was lower. Therefore, these led to the improvement on the inflow conditions of the impeller, was beneficial to increase the efficiency at design flow rate.

![Figure 7. Comparison of velocity distribution on the mid plane.](image1)

![Figure 8. Comparison of velocity distribution on the outlet section.](image2)

To obtain the power spectral density (PSD) of pressure fluctuation at each monitoring point, Fast Fourier transform (FFT) was performed on the pressure fluctuation signal obtained from the numerical simulation. According to the rotational speed of the impeller, the shaft frequency $f_n$ is 48.5Hz, and the blade frequency $f_{BPF}$ is 291Hz.

The location of monitoring points S1 and S2 is shown in figure 9. Figure 10 show the spectrums of pressure fluctuation at the monitoring points S1 and S2 between original model and optimized model. It can be seen from the figure that the main frequency of pressure fluctuation at each monitoring point was the blade frequency. Because the pressure fluctuation in the volute is mainly caused by rotor-
stator interaction between the impeller and the volute, the main frequencies obtained by numerical simulation were all the blade frequency.

![Figure 9. Location of monitoring points.](image)

Figure 9. Location of monitoring points.

![Figure 10. Spectrums of pressure fluctuation at the monitoring points S1 and S2.](image)

Figure 10. Spectrums of pressure fluctuation at the monitoring points S1 and S2.

It can be seen that after optimization, the pressure fluctuation amplitudes at the main frequencies of S1 and S2 were all decreased. The deviations of pressure fluctuation maximum amplitudes at S1 and S2, between original model and optimized model, were 0.89% and 9.15%, respectively. Compared with S2, the fluctuation amplitude at S1 was larger, and there were more high-frequency pulsation components. Through the optimization on the profile of the inlet pipe, the inlet inflow condition of the
impeller was improved, thereby reducing the pressure pulsation in the volute to some extent.

6. Conclusions
In this study, 36 groups of design points on the inlet pipe of vertical inline pump were generated by Latin Hypercube Sampling. CFD code CFX was adopted to solve sample cases to obtain the hydraulic efficiency and unsteady pressure fluctuation at design flow rate. Latin Hypercube Sampling has great property of space filling and reflect the design period. The deviation of the efficiency between original model and optimized model was 2.23%. It can be observed that the profile of inlet pipe has obvious influence on the hydraulic performances of vertical inline pipe at design condition. According to the analysis of velocity distribution on the mid plane and the outlet section between original model and optimized model, the inlet pipe of optimized design became smoother and the velocity distribution on the outlet section was more uniform. These improved inflow conditions of the impeller and decreased hydraulic losses in the impeller and volute. The analysis on the spectrums of pressure fluctuation at the monitoring points between the original model and the optimized model was carried out. The main frequency of pressure fluctuation at each monitoring point were the blade frequency. The deviations of pressure fluctuation maximum amplitude at two monitoring points were 0.89% and 9.15%, respectively. The profile of inlet pipe has a certain impact on the unsteady pressure fluctuation to improve the stable operation of vertical inline pump.

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