Analysis of the Influence of the Number of Torque Converter Blades on Working Performance Based on the Response Surface Method

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Abstract: To understand the effect of the number of torque converter blades on the performance of torque converters, in this paper, we employed computational fluid dynamics and the response surface method to optimize the design of the torque converter. The number of pump blades, stator blades and turbine blades were used as design variables, and the torque transmission ratio and pump capacity factor were used as objective functions for multi-factor optimization design. The results show that the number of turbine blades had no significant impact on the converter’s performance, while the number of pump blades and stator blades had significant impact and showed strong correlation. Compared with the original torque converter, the optimized converter increased the starting torque ratio by 0.12 and the efficiency by 4%. It shows that the computational fluid dynamics and the response surface method can be combined to determine the optimal number of blades in the design of torque converters to reduce the cost and experiment time.

1 Introduction

Due to its good adaptability and stability, the torque converter is widely used in vehicles and construction machinery. Improving the performance of the torque converter has always been a hot research topic. The number of pump blades, turbine blades and stator blades have an important influence on the performance of the torque converter. Therefore, it is of great significance to optimize the number of blades of the torque converter.

In the early days, the design of torque converters mostly used the one-dimensional beam flow theory, simplifying the complex three-dimensional viscous flow in the torque converter into beam motion and using the Euler equation to improve the performance of the torque converter [1]. However, the one-dimensional beam theory makes many assumptions about the fluid properties, resulting in a loss of accuracy in design and optimization [2]. At present, the three-dimensional flow field numerical calculation method is used to simulate the flow field of the torque converter [3–4], thereby further
optimizing the design. Some scholars have found that there is an uneven wake phenomenon at the pump wheel outlet through the single-flow path analysis of the steady-state flow field of the torque converter [5], but the low prediction accuracy cannot be observed in the forward design of the torque converter. Some studies have used numerical simulation to analyze the transient and steady-state flow fields of HTC's and concluded that the transient behavior cannot be obtained through steady-state calculation. Only 3D transient flow calculation can correctly predict the true flow of the fluid [6].

Although there are many studies on the unsteady flow field of the hydraulic torque converter, most of them use the single flow channel flow field analysis method [7-9]. Since the number of pump blades, turbine blades, and stator blades of the torque converter is different, there must be a confluence and diversion between the runners of the torque converter. Since this phenomenon is neglected, the single flow channel flow field is quite different from the actual flow field; the confluence and diversion of the flow field change with the number of vanes of the torque converter. It is necessary to optimize the number of blades of the torque converter, but to obtain the ideal optimization results, the optimization analysis method should be carefully selected.

The response surface method (RSM) is a suitable method for finding optimal experimental conditions related to nonlinear data processing problems. Specifically, it aims to find the optimal combination of conditions in different experiments through experimental design, modeling, model testing and design evaluation. Through the regression fitting of the equation, the response surface analysis and the contour drawing, the response value of each factor level can be obtained. Based on the response value, the optimal response value and the corresponding experimental conditions can be predicted. RSM considers the experimental random error. At the same time, the complex unknown function relationship is fitted in a small area with a simple one or quadratic polynomial model. The calculation is relatively simple and is an effective means to solve practical problems. Compared with the design of experiments (DOE) method which can only analyze one isolated experimental point, RSM can continuously analyze the various levels of the experiment [10-12].

In this paper, the torque converter is taken as the research object, and the working performance of the torque converter is improved. The ANSYS FLUENT numerical simulation method and the response surface optimization method are combined to study the effect of the number of pump blades, turbine blades and stator blades on the performance of the torque converter and find the optimal combination of the number of the blades.

2. Simulation

2.1 Independence of the number of grids
The mesh interface, the computational domain and the grid are shown in Fig. 1.

The torque converter consists of a pump, a turbine and a stator. The number of the pump blades ($N_p$) is 21, that of the turbine blades ($N_t$) is 28, and that of the stator blades ($N_s$) is 17. The pump simulation speed is consistent with the experimental motor speed of 1698 rpm. The working fluid was 6# hydraulic transmission oil, the density was 899.1 kg.m$^{-3}$, and the kinematic viscosity was 0.00189 Pa.s.
The structured meshes of the fluid domains were generated by ANSYS. Mesh models with different mesh numbers were divided by the mesh size, and the same turbulence model (RNG K-ε) and initial conditions (speed ratio: 0.4) were used to verify the grid number independence of the HTC. As shown in Fig. 2, when the number of meshes reaches a certain number, an increase in the number of meshes has no significant impact on the calculation result but increases the calculation time. Considering the balance between solution accuracy and calculation time, the chosen number of calculated grids in this study is approximately 6 million.

Fig. 2 Independence of the number of grids

2.2 Reliability verification
Fig. 3 shows the experimental device used in this research to verify the reliability of the torque converter. A comparison of the experimental data with the CFD simulation results is shown in Fig. 4. Under different speed ratios, the error between the simulated values and the experimental values of the torque ratio and efficiency is less than 5%. There exists a good agreement between the present CFD and experimental results over the wide range of speed ratios.
Fig. 3 Experimental device
(1. Loading motor 3. Driving motor 6. Input torque sensor 14. HTC 20. Output torque sensor 10. Telescopic drive rod 11. Axial displacement drive cylinder; 8 and 18 are support bearings; 4, 7, 9, 12, 13, 19, and 21 are drive chain couplings; 2, 5, 15, 16, 17, 22, 23, and 24 are mounting bases)

Fig. 4 CFD reliability verification

3 Response surface design
The numbers of pump blades, guide blades and turbine blades are taken as the design parameters for response surface analysis. The torque transmission ratio ($K$) and pump capacity factor ($\lambda_p$) are optimized. The performance index is set not less than the initial value of the prototype. An optimization model for different numbers of blades is established.

The torque transmission ratio ($K$) is the ratio of the turbine torque to pump wheel torque, and the pump capacity factor ($\lambda_p$) indicates the ability of the pump blade to absorb input power. 

$$K = \frac{T_T}{T_p}$$
$$\lambda_p = \frac{T_p}{\rho \times g \times n_p^2 \times D^2}$$

where $T_T$ is the turbine torque, $T_p$ is the pump torque, $\rho = 899.1 \text{kg/m}^3$ is the density of the working fluid in the torque converter, and $g=9.8 \text{m/s}^2$ is the acceleration due to gravity, $n_p$ is pump blade speed, $n_p = 1698 \text{ rpm}$, $D$ is effective diameter of the torque converter, $D = 0.265$.

Table 1. Range of the number of blades

|       | Min | Max |
|-------|-----|-----|
| $N_p$ | 17 (-1) | 25 (+1) |
The numbers of blades of the pump, turbine and stator are set as variables, the value range of which is shown in Table 1. A full experimental design would entail $9^3=729$ experiments, which is too time-consuming and unrealistic. In this paper, the most common central composite surface design in the response surface method is used to optimize the design (Fig. 5, $\alpha = 1$). The same computer is used for calculation, which rules out accidental errors, and thus no repeated experiments are set up. The central composite design of Table 1 by Design-Expert software is used to obtain the three factors of pump blades, guide blades and turbine blades. The total of 12 groups of structures in the HTC model were separately modeled to obtain the torque transmission ratio and the pump capacity factor of each structure, as shown in Table 2.

### Table 2 Three-factor numerical calculation result

| $N_P$ | $N_S$ | $N_T$ | $K$ | $\lambda_p$($10^6$) |
|-------|-------|-------|-----|---------------------|
| 1     | 25    | 21    | 28  | 2.955               | 3.310               |
| 2     | 25    | 17    | 32  | 2.761               | 3.520               |
| 3     | 17    | 17    | 24  | 2.820               | 3.340               |
| 4     | 21    | 13    | 24  | 2.464               | 3.761               |
| 5     | 17    | 13    | 28  | 2.462               | 3.581               |
| 6     | 17    | 21    | 28  | 3.191               | 2.828               |
| 7     | 21    | 21    | 32  | 2.836               | 3.310               |
| 8     | 21    | 13    | 32  | 2.446               | 3.641               |
| 9     | 21    | 21    | 24  | 2.865               | 3.340               |
| 10    | 25    | 17    | 24  | 2.733               | 3.611               |
| 11    | 17    | 17    | 32  | 2.777               | 3.370               |
| 12    | 25    | 13    | 28  | 2.437               | 3.791               |

Multiple regression fitting analysis was performed on the data in Table 2, and a quadratic polynomial regression equation with $K$ and $\lambda_p$ as the objective functions was established. The variance of the regression equation was analyzed, as shown in Table 3.

### Table 3 Regression equation analysis of variance

| Source | $K$ Sum of Squares | df | Mean Square | F-Value | Value Prob>F | $10^6\lambda_p$ Sum of Squares | df | Mean Square | F-Value | Value Prob>F |
|--------|-------------------|----|-------------|---------|--------------|-------------------------------|----|-------------|---------|--------------|
|        |                   |    |             |         |              |                               |    |             |         |              |

Fig. 5 Central composite surface design

Table 2 Three-factor numerical calculation result

Table 3 Regression equation analysis of variance
The coefficient of determination \( R^2 = 0.9523 \), \( R^2 = 0.9581 \); and the p values \( P_K = 0.0427 \), \( P_{\lambda p} = 0.0407 \). These indicate that the response value is well fitted and can better explain the experimental results. Table 3 shows that the number of pump blades and stator blades has a significant impact on the pump capacity factor and torque transmission ratio \((P<0.05)\). However, the number of turbine blades has no significant effect.

4 RSM analysis

Fig. 6a shows the influence of the number of turbine and stator blades on the torque transmission ratio. The number of stator blades has a greater influence on \( K \) in the range of 13-21, and that of the turbine blades has less influence on \( K \) in the range of 24-32. As the number of turbine blades changes, the influence of the stator blades on \( K \) remains almost the same. Similarly, as the number of stator blades changes, the impact of turbine blades on \( K \) also remains unchanged. Fig. 6b shows the influence of the number of pump and stator blades on the torque transmission ratio. The number of pump blades has an impact on \( K \) in the range of 17-25, and when the number decreases, the effect of stator blades on \( K \) increases. When the number of stator blades are within the range of 13-17, as the pump blades increases, \( K \) decreases first and then increases. When the number of stator blades are within the range of 17-21, \( K \) increases as pump blades increases. This shows a clear interaction between stator blades and pump blades. Fig. 6c presents the influence of the number of the pump and turbine blades on \( K \). When the number of pump blades gradually decreases, the influence of the number of turbine blades on \( K \) increases. Similarly, as the number of turbine blades increases, the effect of number of blades of pump on \( K \) gradually increases. The impact of the number of both the pump blades and the turbine blades, however, is small.
Fig. 7 shows the influence of multiple factors on \( \lambda_p \).

(a) Influence of \( N_T \) and \( N_S \) on \( \lambda_p \)
(b) Influence of \( N_P \) and \( N_S \) on \( \lambda_p \)
(c) Influence of \( N_T \) and \( N_P \) on \( \lambda_p \)

Fig. 7a shows the influence of the number of turbine and stator blades on the pump capacity factor. The number of turbine blades and stator blades has the same effect on pump capacity factor as on the torque transmission ratio. They have interactions: when the number of stator blades is small, the impact of the number of turbine blades on \( \lambda_p \) becomes more tangible; Similarly, when the number of turbine blades is small, the number of stator blades has a more pronounced effect on \( \lambda_p \). Fig. 7b shows the influence of the number of stator and pump blades on the pump capacity factor. The number of stator and pump blades has an obvious impact on pump capacity factor. When pump blades are less, stator blade has a greater impact on \( \lambda_p \); when the number of stator blades is small, as the pump blades increase, \( \lambda_p \) increases first and then decreases. When the number of stator blades is large, \( \lambda_p \) increases as the pump blades increase. Fig. 7c shows the influence of the number of turbine and pump blades on \( \lambda_p \). The interaction between pump blades and turbine blades is also weak. When the number of pump blades is large, the number of turbine blades has a slightly greater influence on \( \lambda_p \). When the number of turbine blades is more, the number of pump blades has a slightly greater influence on \( \lambda_p \).

The same problem exists in the number of pump blades, stator blades and turbine blades: the flow path area increases as the number of blades decreases, resulting in an increase in the pressure gradient and thickening of the boundary layer, which ultimately undermines the performance of the torque converter. Similarly, when the number of blades is too large, it may cause blockage of the inlet and outlet of the flow passage, and increase the frictional loss of fluid flow in the flow passage, and the performance of the torque converter will also decrease. Therefore, the number of blades is very important in the design of torque converters. Similarly, to improve the performance of the torque converter is considered, not only the torque transmission ratio but also the pump capacity factor should be considered. Thus, a good torque converter needs to have a higher torque transmission ratio and a higher pump capacity factor.

5. Optimization Results

By performing response surface analysis on Tables 2 and 3, the software predicts the optimal number of blades, torque transmission ratio and pump capacity factor. The predicted new torque converter, the grid, flow field calculation, torque transmission ratio and pump capacity factor are modeled at a speed ratio of 0 \( (i=0) \), as shown in Table 4.

| Model          | \( N_P \) | \( N_S \) | \( N_T \) | \( K \)  | \( T_p \) |
|----------------|----------|----------|----------|--------|---------|
| Original-Estimate | 21       | 17       | 28       | 2.825  | 3.334   |
| Original-CFD    | 21       | 17       | 28       | 2.855  | 3.365   |
| New-Estimate    | 25       | 20       | 24       | 2.952  | 3.484   |
| New-CFD         | 25       | 20       | 24       | 2.975  | 3.501   |

As Table 4 shows, the error between the response surface estimation result and the simulation result is within 0.5%, which indicates that the response surface method has high precision and is suitable for optimizing the model. It can be seen from Fig. 8 that though new HTC increases the number of pump
blades and stator blades, and it reduces the number of turbine blades; compared to original HTC, the new HTC’s starting torque ratio increases by 0.12 and its efficiency increases by 0.04.

Fig. 8 Performance comparison between original HTC and new HTC

6 Conclusion
Based on the three-dimensional flow design, this study combined RSM and CFD to study the influence of the number of blades on the performance of the torque converter, and the optimal design of the number of blades of the torque converter is realized.

1) Flow field simulation of the torque converter shows that the error between the simulation performance and the experimental performance is less than 6%. This suggests that using CFD to simulate the 3D transient full-path simulation of the torque converter can get close to the experimental results.

2) Through multi-factor analysis of the torque converter blades, it is concluded that each blade has different degrees of impact on the torque transmission ratio and the pump capacity factor. The interaction between stator blades and pump blades is the most obvious, and turbine blade has the weakest effect on the performance of the torque converter.

3) RSM is used to estimate the optimal structure to obtain the new HTC, where \( N_p=25, N_s=20, N_t=24 \). Compared to the original HTC, the new HTC’s starting torque is increased by 0.12, its efficiency increased by 0.04. It shows that RSM has high precision in the optimization of the number of blades of the torque converter.

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