Hydrodynamic optimization of trust ring pump and lubricating oil system for large hydroelectric units thrust bearing

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Abstract. Thrust-ring-pump is a kind of extreme-low specific speed centrifugal pump with special structure as numerous restrictions form thrust bearing and operation conditions of hydro turbine generator unit. Because the oil circulating and cooling system with thrust-ring-pump has a lot of advantages in maintenance and compactness in structure, it has widely been used in large and medium-sized hydro-generator units. Since the diameter and the speed of the thrust ring is limited by the generator set, the matching relationship between the flow passage inside the thrust ring (equivalent to impeller) and oil bath (equivalent to volute) has great influence on hydrodynamic performance of thrust-ring-pump, additionally, the head and discharge are varying with the operation conditions of hydro-generator unit and characteristic of the oil circulating and cooling system. As so far, the empirical calculation method is employed during the actual engineering design, in order to guarantee the operating performance of the oil circulating and cooling system with thrust-ring-pump at different conditions, a collaborative hydrodynamic design and optimization of both the oil circulating and cooling system and thrust-ring-pump is purposed in this paper. Firstly, the head and discharge required at different conditions are decided by 1D flow numerical simulation of the oil circulating and cooling system. Secondly, the flow passages of thrust-ring-pump are empirically designed under the restrictions of diameter and the speed of the thrust ring according to the head and discharge from the simulation. Thirdly, the flow passage geometry matching optimization between holes inside the thrust ring and oil bath is implemented by means of 3D flow simulation and performance prediction. Then, the pumps and the oil circulating and cooling system are collaborative hydrodynamic optimized with predicted head-discharge curve and the efficiency-discharge curve of thrust-ring-pump. The presented methodology has been adopted by DFEM in design process of thrust-ring-pump and it shown that can effectively improve and guarantee the performance of the oil circulating and cooling system.

1. Introduction
Thrust bearing is one of the most important components for hydraulic turbine-generator units, and it’s lubricating and cooling systems is essential for thrust bearing and even for keeping normal operation of the whole hydraulic turbine-generator. Because the oil circulating and cooling system with thrust-ring(or cone) -pump has a lot of advantages in maintenance and compactness in structure[1], it has
become a trend to use this kind of self-pumped thrust ring pump to increase oil circulating pressure for lubricating and cooling systems of large and medium-sized hydro-generator in recent years \[2-5\].

Thrust-ring-pump obtains similar function of centrifugal pump with several holes (similar to impeller passage) drilled inside the thrust ring or thrust cone and the oil bath (equivalent to volute) installed at outer edge of the thrust ring or thrust cone. The speed of thrust-ring-pump is determined by the rotating speed of hydraulic turbine, and the dimension and structure of the thrust ring or thrust cone are limited by the structure of the generator. The holes pattern should be selected to ensure convenient in manufacturing, and it also must take into account that the influence form geometries and number of the hole on strength of thrust ring or thrust cone. However, the layout of hole pattern and number of holes inside the thrust ring or thrust cone, and the shape, area, outlet pipe diameter of oil bath and other geometric parameters have great influence on hydrodynamic performance of thrust-ring-pump. In theory, although thrust-ring-pump is a kind of centrifugal pump which has very special structure with numerous restrictions, the traditional design theory and method for centrifugal pump aren’t fully applicable for this kind of extreme-low specific speed centrifugal pump. As so far, the hole inside the thrust ring or thrust cone is designed in the radial and backward direction, and the “head-discharge” curve of thrust-ring-pump is assumed as a parabola curve to approximately calculated the pump’s head. Meanwhile, the oil bath is mainly been taken as a device to collect oil from outlet of the thrust ring holes and transport oil to the outlet of the lubricating and cooling pipe and its hydrodynamic performance isn’t much been considered in actual engineering. This design methodology often leads to poor hydrodynamic performance for thrust-ring-pump \[6-9\].

In this paper, to the optimize the layout and number of holes and geometric parameters such as hole’s shape, area, outlet pipe diameter of oil bath in hydrodynamic design of thrust-ring-pump, the influence form geometric parameters on hydrodynamic performance of thrust-ring-pump has been numerically simulated and analysed under the constraint condition of manufacture and strength of thrust ring or thrust cone. The feasibility of the hydrodynamic performance prediction method for thrust-ring-pump by means of multi-condition numerical simulation has been verified by combining a test model of thrust-ring-pump for a large hydroelectric units thrust bearings. Grouping the different geometric parameters, the influence from flow passages geometric parameters on hydrodynamic performance of thrust-ring-pump can be analysed and predicted by the verified performance prediction method, and the influence from the key dimensions and the shape of flow passage on the pump have more deeply analysed. By this way, a performance prediction and optimization design method suitable for the flow passages of thrust-ring-pump has been explored, and it has been provided a theoretical foundation and effective technical approaches for optimization design of thrust-ring-pump and lubricating and cooling systems of the thrust bearings.

2. Numerical simulation for characteristics of lubricating cooling systems and determination of design parameters of thrust-ring-pump

2.1. Lubricating and cooling systems for thrust bearings with thrust-ring-pump

Because the thrust load and the cooling discharge for a large hydro turbine generator is very large, the internal structure of thrust bearing can be greatly simplified by applying external circulation cooling system, and which has the advantage of disassembling thrust ring without disassembling the oil cooler, easy in maintaining thrust bearing and oil cooler, and repairing single oil cooler without influencing the use of other coolers \[1\]. In recent years, it has widely applied thrust-ring-pump to replace the additional pump located outside the lubrication oil reservoir in the external circulation cooling system for a large and medium-sized hydro turbine generator if the pressure can be increased more than 0.1Mpa by the way of self-pumping \[6\]. The discharge and pressure of circulating oil for thrust bearing circulating and cooling systems self-pumped by the thrust-ring-pump should be matched with pipe characteristic of lubricating and cooling systems. In the thrust-ring-pump design, firstly design parameters of thrust-ring-pump should be determined with numerical simulation of pipe characteristic on the basis of the layout of lubricating and cooling systems, or by adjusting the pipe characteristic
obtained from numerical simulation to meet the requirements of operation parameters of thrust-ring-pump in actual engineering. Figure 1 shows the lubricating and cooling pipe systems of test-bed for verifying performance of the thrust-ring-pump, the pressure oil from the thrust-ring-pump flow into the cooling systems which includes four coolers through a loop pipe.

![Image of lubricating and cooling pipe systems](image1)

**Figure 1.** The lubricating and cooling pipe systems of test-bed

2.2 Numerical simulation for hydraulic loss of lubricating and cooling systems and verification

The self-pumped oil circulating and cooling system consists of a thrust-ring-pump, several oil coolers, valves, bend, junction, pipes and so on. The layout and installation elevation of oil coolers, valves and pipes are varying in different hydropower stations, and the pressure provided by thrust-ring-pump is also different. During the design of thrust-ring-pump, as the restriction of the size of thrust bearing and the speed of unit, if parameters of the pump can’t be satisfied after calculation, you also can adjust the loss characteristic of components in the oil circulating and cooling system to meet the requirements of the thrust-ring-pump, so it is very important to accurately numerical simulate and optimize the pipe characteristics of lubricating and cooling systems. The one-dimensional hydrodynamic simulation for the oil circulating and cooling system of thrust-ring-pump test-rig has been conducted with Flowmaster® software, and figure 2 shows the model of the system in Flowmaster® software. In order

![Image of simulation model](image2)

**Figure 2.** The simulation model of the cooling system in Flowmaster®

![Image of results comparison](image3)

**Figure 3.** The results comparison between the test the data and simulation data
to verify the accuracy of the numerical simulation, the pipe characteristic tests of the oil circulating and cooling system of thrust-ring-pump test-rig has been conducted for systems with one, two, three oil coolers respectively at DFEM (Dongfang Electric Machinery Co. Ltd.), and figure 3 shows the results obtained from both of the test and simulation.

2.3. Determination of hydrodynamic parameters for thrust-ring-pump

It can provide accurate hydrodynamic parameters for the design of thrust-ring-pump after the hydrodynamic loss characteristics of the oil circulating and cooling system of thrust bearing has been calculated with numerical simulation as shown in figure 2.3. Moreover, you can adjust the loss characteristic of components in the oil circulating and cooling system to match design parameters of the thrust-ring-pump by optimization the pipe characteristic of lubricating and cooling systems of thrust bearing.

According to the figure 3 and the unit with speed of 225 r/min, the hydrodynamic parameters of the thrust-ring-pump has been defined as: the discharge of 124 m$^3$/h, the head of 20 m.

3. Hole pattern inside thrust ring and the influence on the hydrodynamic performance of thrust-ring-pump

The structure and size of thrust bearing have been determined during the design of the hydro turbine-generator, and the inner and outer diameter of the thrust ring is Ф1040mm and Ф2139mm respectively. According to the requirement for hydrodynamic parameters, the preliminary flow passages of the thrust-ring-pump (hereafter called scheme A) has been designed by means of the basic theory for centrifugal pump. This scheme has the following features: the holes inside thrust ring are radial straight holes with the diameter of Ф40 mm and the number of 8; the oil bath has the base circle diameter of Ф2296 mm with the inlet width of 65 mm and total outlet area of 24531 mm$^2$. The cross-sectional shape of oil bath is rectangular, with exterior lines of logarithmic spiral, and eight outlets is arranged evenly at circumferential direction. The 3D model of flow passages of thrust-ring-pump is shown in figure 4 (a).

3.1. Hole patterns inside thrust ring

In order to optimize the design of the hole patterns inside thrust ring, on the basis of the preliminary design of radial straight hole patterns (scheme A), taking account to the limitations of structural strength and manufacturing, another 5 kinds of hole patterns were designed for the above-mentioned thrust ring, the comparative study was conducted among the 6 schemes. The table 1 lists the different parameters of the 6 schemes (labelled as A, B, C, D, E, F), and their 3D models are shown in figure 4.

Table 1. The features of the 6 kinds of scheme.

| Scheme | Hole central line | The sectional shape of holes | Passage features |
|--------|------------------|-----------------------------|-----------------|
| A      | radial line      | Circular                    | All holes are radial straight hole |
| B      | Inclined line    | Circular                    | Drilling straight holes on the thrust ring, the most small Outlet angle is 61° |
| C      | Multi-line (one outlet) | Circular                  | Outlet angle is 61°, inlet angle is 90° |
| D      | Multi-line (two outlet) | Circular                    | Outlet angle of inclined hole is 61°, another hole is radial straight hole |
| E      | Arc -line (outlet angle of 61°) | Square                   | Outlet angle is 61°, inlet angle is 90° |
| F      | Arc -line        | Square                      | Outlet angle is 20°, inlet angle is 90° |
3.2. 3D models of six scheme’s thrust-ring-pump

Figure 4 shows 3D flow passage models of the six scheme’s thrust-ring-pump combining with the same oil bath and pipes.

(a) scheme A  
(b) scheme B 
(c) scheme C  
(d) scheme D
3.3. Hydrodynamic performance analysis for the six scheme’s thrust-ring-pump

The flow inside the passage of the six scheme’s thrust-ring-pump had been numerically simulated with ANSYS/CFX® software. During numerical simulation, as the thrust ring is rotating part and inlet and oil bath are static, “Frozen-Rotor” and “Transient Rotor-Stator” models were respectively adopted in steady state and transient flow numerical simulation with RNG k-Epsilon turbulence model and wall function method. Time step was setup $1.667 \times 10^{-3}$ for transient flow numerical simulation. On the basis of numerical simulation, the external performance curves of the thrust-ring-pumps of the six scheme’s thrust-ring-pump were predicted and shown in figure 5.

Figure 4. Three-dimensional models of thrust-ring-pumps with different hole patterns.
In order to further analyse the different passage’s influence on hydrodynamic performance of the thrust-ring-pumps, the thrust-ring-pump is divided into thrust ring and oil bath form viewpoint of energy conversion. The efficiency of thrust ring and oil bath is shown respectively in figure 6 and 7. The efficiency is defined as the ratio of output energy and input energy of thrust ring or oil bath. Figure 6 shows that the efficiency vary with discharge of thrust ring, and the efficiency curves of six schemes are ordered from high to low as : scheme B>A>E>C>D>F, while the efficiency curves of scheme B is much higher than others. Figure 7 shows that the efficiency vary with discharge of oil bath, it is noticed that the efficiency curves of six schemes are ordered from high to low as: F>B>C>E>D>A, all efficiency curves of oil bath have great difference in the variation trend, the efficiency of scheme F and B increases gradually along the increases of the flow-rate, and the efficiency curves of scheme C, E and D are more flat along the increases of the flow-rate, while the efficiency of scheme A decreases gradually along the increases of the flow rate.

4. Influence of geometrical parameters of oil bath on thrust-ring-pump’s performance
As mentioned above, the performance of oil bath has not much been considered in actual engineering design, while it is mainly been taken as a device to collect oil from the outlet of thrust ring holes and transport it to lubricating and cooling pipes. From the above analysis, it should be noted that the oil bath is equivalent to volute of ordinary centrifugal pump, so the hole pattern inside thrust ring must match with flow passages of oil bath as the geometrical parameters of oil bath have great influence on thrust-ring-pump’s performance. In another words, Oil bath is one of the most important parts of
thrust-ring-pump, its flow passage must match with the holes pattern inside thrust ring in design. The influence form cross-sectional shape and outlet area of oil bath on thrust-ring-pump’s performance have been below estimated by means of flow numerical simulation and analysed in the followings.

4.1. **Cross-sectional shape of oil bath**

On the basis of the original oil bath with rectangular (RET) cross section, additional two kinds of oil bathes with trapezoidal (TRA) and circular (CIR) cross-sectional were designed under the same area. The oil bathes were designed with the law of constant velocity in all cross sections over the circumference, except cross-sectional shape, other geometrical parameters of oil bath are in accordance with that of thrust-ring-pumps with different hole patterns inside the thrust ring. Three kinds of cross-sectional shape are shown in figure 8.

![Cross-sectional shapes](image)

Figure 8. Three kind of cross-sectional shape.

Combining 3 kinds of cross-sectional shape oil bathes with 6 kinds of hole patterns inside the thrust ring, we can generate 18 thrust-ring-pump’s flow passage models as listed in Table 2.

| Model. No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|------------|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|
| hole pattern | A | A | A | B | B | B | C | C | C | D | D | D | E | E | E | F | F | F |
| Oil bath   | R | T | C | R | T | C | R | T | C | R | T | C | E | R | I | E | R | E | R | I |
|            | T | A | R | T | A | R | T | A | R | T | A | R |

3D flow numerical simulation and external performance predicted had been conducted for 18 thrust-ring-pump’s flow passage models as listed in Table 2. It shown that when the 6 kinds of hole patterns inside thrust ring match with rectangular and circular cross-sectional oil bathes, there are only tiny differences in the pressure and the efficiency of 6 kinds of hole patterns inside the thrust ring pumps. Only when the 6 kinds of thrust ring holes match oil bath with trapezoidal cross-sectional oil bathes, the head and efficiency go down small, especially near low 5% comparing with rectangular and circular cross-sectional oil bathes at the condition of small discharge. Thus it can be shown that the cross-sectional shape of oil bath has only tiny impact on the thrust-ring-pump’s performance, and oil bath with rectangular and circular cross-sectional are recommended to be adopted in design.
4.2. Outlet area of oil bath

The outlet diameter of oil bath is one of the geometrical parameter closely relating to thrust-ring-pump’s hydrodynamic performance, the outlet diameter of oil bath for the original test pump model (scheme A) is Φ65 mm. In order to analyse the impact of outlet area of oil bath on thrust-ring-pump’s performance, we assumed that the outlet area is changed into half and double of the original and the corresponding outlet diameter are Φ46 mm and Φ92 mm respectively. Excepting the outlet area of oil bath, the other geometrical parameters of model are unchanged.

![Figure 9](image)

**Figure 9.** Performance curves of thrust-ring-pumps with different outlet areas.

The predicted external performance curves by means of 3D flow numerical simulation are shown in figure 9 for thrust-ring-pumps with outlet diameter of Φ46 mm (D46), Φ65 mm (D65) and Φ92 mm (D92). From figure 9(a) and figure 9(c), it can be seen that the head and efficiency of the pump increase greatly if outlet diameter of oil bath is Φ46 mm, while the head and efficiency of the pump decrease a little if outlet diameter of oil bath is Φ92 mm. From the figure 9(b), it is noticed that the shaft power increases a little as outlet area reduces half, while the shaft power almost no change as outlet area increases one time.

5. The optimization design of thrust-ring-pump for one large hydroelectric units thrust bearing

Based on the above calculation and analysis, the flow passage of original test pump model (scheme A) has been optimized. To guarantee thrust-ring-pump’s hydrodynamic performance, the holes inside thrust ring must match oil bath well, so the size of oil bath at axial direction shouldn’t be too small and should be larger than the diameter of holes inside thrust ring at least. Since the diameter of the holes inside thrust ring is Φ40mm, the outlet diameter of oil bath was set Φ50 mm and gradually increases...
up to Φ92 mm after 3D flow numerical simulation and performance prediction of multi-scheme thrust-ring-pump had been conducted. In order to further reduce the total area of oil bath and simplify the structure, the number of outlet is decreased from 8 to 2. In this way, it can not only ensure the size of oil bath at axial direction, but also reduce the total area of oil bath and simplify its structure. Figure 10 shows 3D model of optimized flow passages. Figure 11 shows the performance curves of both before and after optimization, and it proved that the performance of optimized thrust-ring-pump has greatly enhanced.

![Image](image.png)

**Figure 10.** Three-dimensional model of optimized flow passages.

![Graph](graph.png)

**Figure 11.** Performance curves of both before and after optimization.

### 6. Conclusion

Thrust-ring-pump is a kind of extreme-low specific speed centrifugal pump which has very special structure with numerous restrictions form thrust bearing and operation conditions of hydro-generator unit. It should not only focus on itself but also take the pipes and other components of circulating and cooling systems into account during the design of thrust-ring-pump. A collaborative hydrodynamic optimization methodology for thrust-ring-pump and the oil circulating and cooling system has been presented with 3D flow numerical simulation and performance prediction. For design of a thrust-ring-pump, you should pay attention to:

1. To accurately determine the hydrodynamic parameters for the design of thrust-ring-pump, the hydrodynamic loss characteristics curves of the oil circulating and cooling system of thrust bearing should firstly calculated with 1D flow numerical simulation based on the layout of oil lubricating and cooling systems system for hydro turbine units at the power plant.
(2) Although there has some differences in the performance curves between the prediction based on 3D flow numerical simulation and the test results, it is feasible to use the numerical simulation technology to analyse and optimize the flow passage of thrust-ring-pump.

(3) The flow passage matching between the holes inside thrust ring and oil bath has great impact on thrust-ring-pump’s hydrodynamic performance. In the design of oil bath, you can select the cross-sectional shape of oil bath by only considering convenient in manufacturing. If the structure allows, the total area of oil bath should be reduce properly. In order to reduce the hydrodynamic losses, the type and diameter of outlet pipe should be chosen carefully.

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