Automatic Design of Hydraulic Manifold Block Based on 3D Printing

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Abstract. Aiming at the problem of structural and internal quality optimization bottlenecks caused by the limitation of traditional machining capacity, the automatic design method of hydraulic manifold blocks (HMB) based on 3D printing is designed. According to the processing capability of complex parts and the production economy of small batch production, the typical hole structure of HMB is optimized with the support of 3D printing and evaluating of fluent simulation and experiment. A set of hole design rules was put forward and the automatic design of HMB based on the intelligent optimization algorithm was realized. The design method is verified by engineering design examples, which provides a reference for the further optimization of the structure and internal quality of HMB.

1. Introduction

The hydraulic manifold block acts as a carrier for connecting the piping and valve components of the hydraulic system, and plays an important role in the hydraulic system with features such as high degree of integration and ease of maintenance. However, a series of problems such as hole network pressure loss, temperature rise and noise caused by the typical hole structure inside the manifold block have a bad influence on the reliability and life of the system. At the same time, pressure loss is also one of the key factors affecting the efficiency of the hydraulic system [1]. Studies have shown that the average efficiency of the industrial hydraulic system is 50%, while the average efficiency of the walking machine is 21% [2]. These factors lead to the fact that the manifold block meets the connectivity requirements in terms of structure, but it cannot meet the requirements of system design and use in terms of performance [3].

At present, the research on hydraulic manifolds at home and abroad is not limited to the requirements of structural connectivity, but it pays more attention to the requirements of flow quality. However, due to the limitations of traditional processing methods, the internal hole of the hydraulic manifold is still dominated by straight holes, accompanied by a small number of inclined holes, which does not fundamentally solve the problems of large energy loss and temperature rise of the hydraulic manifold. 3D printing's powerful ability to process complex parts can not only process closed internal flow channels, but also accurately process complex shaped cross-sections based on flow field simulation results [4]. There have been studies abroad using 3D printing technology to manufacture hydraulic manifolds. For example, Renishaw proposed the use of 3D printing technology to redesign hydraulic manifolds and achieved good results [5].

However, in order to improve the performance of the flow path, a large number of complex shaped structures will appear in the hydraulic manifold. It leads to the design of using existing CAD systems will be very complex and time-consuming, and also difficult to ensure the quality of the design.
Therefore, for the 3D printing manufacturing manifold, the difficult problem is to complete the automatic optimization design of the hydraulic manifold block quickly and with high quality.

2. Traditional hydraulic manifold analysis

Traditional hydraulic manifolds mainly process their internal tunnels through drilling, expansion, and reaming. Therefore, there are inevitably structures such as right-angled corners, process cavity, and sudden change in radius, which will result in the performance and reliability of hydraulic components and the entire system. A great deal of influence is analyzed as follows:

2.1. Pressure loss

In the hydraulic manifold, the structures that cause local pressure loss mainly include right-angled turning holes, stepped holes, and Z-shaped holes. The fluid forms vortices at the inner corners of the right-angle turn, and the flow lines of the fluids are separated from the inner corner walls, resulting in separation losses [6]. The liquid flow forms a high pressure zone at the step boundary, while the center pressure is small, and two “whirlpools” form inside the sidewall. The huge pressure in the vortex zone is the root cause of local pressure loss [7]. Studies have shown that, under the same boundary conditions, the pressure loss in the Z-shaped hole is greater than the sum of the pressure losses of the two right-angle holes [6].

The pressure loss caused by a large number of right-angle turnings and stepped structures formed by tens or even hundreds of holes in a hydraulic manifold can not be ignored.

2.2. Transmission accuracy

With the application of proportional control, servo control and digital control technologies in the hydraulic field, higher requirements have been put forward for the inflow quality of the hydraulic system. Hydraulic manifolds serve as carriers for these high-precision components, and their criss-crossing internal holes adversely affect fluid performance. If the closed-loop servo feedback parameter is taken at the turbulent flow, or as the value of the high-precision sensor, the value will be inaccurate or fluctuate, which will greatly affect the accuracy of the hydraulic system [9].

2.3. Temperature rise

The main form of energy loss is heat, which causes the temperature of the hydraulic system to rise and thus brings a series of problems. The data shows that the stable service life of mineral oil will be reduced by 90% for each temperature increase of 15°C; the extremely unfavourable effect of temperature rise on the medium is also due to the decrease of viscosity and lubricating performance, which brings certain difficulties to the sealing of the high pressure system. Temperature rise will cause the part to expand, coupled with poor lubrication, it will cause action failure and control failure [10].

3. Fluent simulation analysis and experimental verification

This section uses a basic eccentric right-angle turning structure to compare the results of Fluent simulations and experimental measurements in order to verify the feasibility of Fluent's simulation analysis of the performance of the manifold hole.

Figure 1(a) shows the common hole structure in the manifold block. To avoid interference, the centralines of the two holes do not lie on the same plane. The main reasons affecting the performance of eccentric-type holes are the eddy currents formed by the abrupt turn and cross-sectional flow area abrupt changes. Therefore, in the case where the centreline is not coplanar, we use a smooth connection of different sides to reduce the pressure loss in the hole, as shown in Figure 1(b).
First, fluent simulation is used to analyze both types of holes. Set flow import and pressure outlet boundary conditions (outlet pressure 2MPa). Table 1 shows the pressure loss results of the two structures simulated at different import flow.

| Import Flow (L/min) | Pressure Loss in Machining Hole (kpa) | Pressure Loss in 3D Printing Hole (kpa) |
|---------------------|--------------------------------------|----------------------------------------|
| 0.7                 | 6.3                                  | 2.6                                    |
| 1.05                | 11.5                                 | 5.2                                    |
| 1.4                 | 17.9                                 | 7.5                                    |
| 1.75                | 27.7                                 | 9.5                                    |
| 2.1                 | 36.9                                 | 10.9                                   |

In order to verify the Fluent simulation results, the above geometry was 3D printed and tested. The experiment was conducted in the hydraulic laboratory of Dalian University of Technology and used the Bosch Rexroth DS4 experimental bench. The experimental apparatus for measuring pressure loss is shown in Figure 2.

Figure 3 compares experimental and simulated pressure loss for a traditional machined hole and a 3D printed hole. It is a good indication that the 3D-printed smooth transition hole can effectively reduce the pressure loss compared to a typical right-angled eccentric structure. Based on this, the constraints on the structure and performance of the manifold block design can be significantly reduced.

At the same time, comparing the simulation curve with the experimental curve, it can be known that the simulated pressure loss and the experimental results have a high degree of fitting. It can fully reflect the correct trend of pressure loss in different structural holes. This allows the establishment of a clear dependency between pressure loss, flow and geometry, and then evaluates the performance of the hole structure.
4. Design method based on 3D printing
This section uses Fluent simulation to analyze the common hole forms in hydraulic manifolds. According to the fluid flow characteristics, it proposes corresponding structures to improve the dynamic characteristics of the hole network. Relying on the flexible processing capability of 3D printing, the internal hole structure of the manifold is redesigned with the inward flow quality as the guide. To facilitate the observation of the pressure drop, the simulated import speed was adjusted to 10 m/s, and the remaining conditions were the same as in Section 3. The design work goes from the following three aspects.

4.1. Remove process cavity
The process cavity is a result compromised by the limitations of traditional machining capabilities. As shown in Figure 4, after the process cavity is removed, the pressure loss drops from 0.24 MPa to 0.2 MPa.

![Figure 4. Pressure cloud before and after removing process cavity](image)

The reason is that the vortex effect produced by the process cavity disappears and the fluid flow characteristics are improved. At the same time, the reduction of the total length of the hole will also reduce the volume of the integrated block, and accordingly the weight of the integrated block will also decrease.

4.2. Arc transition
Studies have shown that in the same diameter and length dimensions, the value of the liquid resistance in the circular turning hole is 75% lower than that of the right-angle turning hole [3]. Figure 5 shows the pressure cloud for the different corners of the hole.

![Figure 5. Pressure cloud of right angle turn, 1.5 times diameter round and 2 times diameter round](image)

The pressure loss of each hole is 0.124MPa, 0.093MPa and 0.083Mpa. It respectively indicates that the arc transition can effectively reduce the pressure loss. It also shows that the larger the radius of the arc, the lower the liquid resistance of the flow path, and the less the system's non-functional consumption.

4.3. Continuously changing radius
When inevitably a sudden change in the radius of hole connection occurs, continuously changing radius should be used instead of a stepped hole to form a smooth, streamlined transition. Figure 6 shows a pressure-cloud diagram of the transition from 10 mm to 6 mm in diameter.

![Figure 6. Pressure cloud of radial mutation hole and radial gradient hole](image)
Table 2 shows the pressure loss when different diameters are connected to each other. It can be seen that as the radius changes, the advantages of gradient holes become more and more obvious.

| D1-D2(mm) | Pressure loss of mutation hole (MPa) | Pressure loss of gradient hole (MPa) |
|-----------|-------------------------------------|-------------------------------------|
| 8-6       | 0.187                               | 0.161                               |
| 10-6      | 0.497                               | 0.401                               |
| 12-6      | 1.081                               | 0.825                               |

5. Automatic design program and application examples

After years of accumulation, our research group has developed a traditional hydraulic manifold block automatic optimization design program \[^{[11]}\]. Keeping the basic structure of the program unchanged, combined with the above analysis of the paper, an automatic optimization design module of manifold block based on 3D printing was developed. The program uses a new set of hole connectivity rules and adds transitional process holes, using AutoCAD2014 and ObjectARX2014 as development platforms.

In the following, a plate-type valve hydraulic system is used as an example to perform optimized design of the hole connection. The system principle is shown in Figure 7.

![Figure 7. Hydraulic schematic](image)

1. Constant delivery pump 2. Relief valve 3. Throttle valve 4. 2-position 2-way reversing valve 5. 2-position 3-way reversing valve 6. 2-position3-way reversing valve 7. hydraulic cylinder

The traditional design and the 3D printing design are automatically calculated at the same time, and the three-dimensional assembly drawing of the optimization result is shown in Figure 8. The calculation results are shown in Table 3.

![Figure 8. Comparison of the results of machine and 3D printing](image)

|                          | Machining design | 3D printing design |
|--------------------------|------------------|-------------------|
| Calculating time         | 10 mins          | 10 mins           |
| Number of iterations     | 132              | 160               |
| Volume                   | $7.67 \times 10^6 \text{mm}^3$ | $4.7 \times 10^6 \text{mm}^3$ (25.1% reduction) |
| Number of process hole   | 8                | 0                 |
| Length of hole network   | 2011 mm          | 1507 mm (38.7% reduction) |
| Pressure loss of typical hole | 0.1887         | 0.0479 (74.6% reduction) |
The new design has no actual process holes, and the total length of the hole network and the volume of the manifold have been reduced by 25.1% and 38.7%, respectively, achieving the goal of further optimizing the structure. At the same time, the number of new iterations of the new program is more, which improves the calculation speed of the program. After Fluent simulation analysis, the total pressure loss of the network based on 3D printing is reduced by 74.6%.

6. Conclusion
After Fluent simulation analysis, experiment and engineering design example verification, hydraulic manifold automatic optimization method based on 3D printing is an effective way to improve the hydraulic manifold design efficiency and design quality. The total network length and volume of the manifold block in the example is reduced by 25.1% and 38.7% respectively, and the pressure loss of the typical wire network was reduced by 74.6%, achieving the goal of structural and performance optimization.

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