The optimization design algorithm of hydraulic components under multiple operating conditions

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With the rapid development of industry, the dynamic performance of hydraulic components has drawn more and more attention /1/. In many hydraulic systems, it is difficult to optimize the designs of the flow components because of many complex parameters and dynamic flow field/2/. At the same time, it is necessary to find out the key structure areas that affect the relevant hydraulic performance and ensure that multi-parameters are optimized synchronously. In this study, the multi-conditions optimization design algorithm is proposed to achieve the optimization of hydraulic components (for example, the throttle valve) by combining the adjoint method and the mesh deformation technique.

Keywords: Optimization, adjoint method, mesh morphing, multiple conditions
Target audience: Design Process

1 Introduction

Many fluid machines have a variety of working conditions, such as the valve at different openings. And control valve characteristic curves and pump dynamic characteristics are both the main performance indicators. Therefore, we need to focus on these performance in the design of these fluid machines. The core of the optimization problem is how to establish the relationship between structural parameters and performance requirements of hydraulic valves /3/. Most of traditional methods are based on stochastic optimization algorithm, and the optimal model is selected by filtering the throttle characteristic data of different parameter models /4/. These traditional methods are mainly based on experience or stochastic optimization. The disadvantage of these methods is blindness, which takes a lot of computing time. Gradient-based algorithms guide the direction of optimization, which is widely applied in aerodynamics. The adjoint method, which was proposed by Pionneau /10/, offers an efficient alternative for computing gradient. With the method of adjoint method, the gradient between performance targets and structural parameters is obtained in only two steps, the primal solver and the adjoint solver. The performance index of this study is dynamic performance, which is manifested in different working conditions. Dynamic performance is the multi-objective performance under various working conditions. In fluid calculations, this problem requires the dynamic grid technology because of the changing of fluid boundary. By adjoint method, the gradient of the fluid boundary mesh for each working state is calculated. In order to achieve optimal deformation of the fluid machine, it is necessary to ensure that the mesh topology on the boundary under different states keep in accordance. Radial Basis Function(RBF) mesh deformation method has been widely used in CFD simulations with moving boundaries due to its high robustness and accuracy/9/. RBF morphing can transform the surfaces of the original model into a new position or shape. In this study, RBF morphing is used not only for rigid dynamic motion but also for optimizing deformation.

The purpose of the study is the establishment of the gradient relationship between throttle valve structure parameters and the flow characteristic curve/5/. The amount of changes in the optimization parameters is quantified by means of computational fluid dynamics. According to the working characteristics of the throttle valve, this study presents the multi-conditions optimization design algorithm combing adjoint solver and Radial Basis Function(RBF) mesh deformation technology. Compared to the generalized optimization design, the optimization strategy in this paper not only reduces the time and cost, but also directly finds out how key parts affect the performance under multiple operating conditions, and it can be also applied to the design of other fluid mechanical components.

2 Methodology

2.1 Adjoint method

An adjoint method can be applied to elegantly compute the sensitivities of the cost function wrt. each mesh cell, which can be fed into a gradient-based optimization algorithm/8/. The constraint of the flow domain in a optimization problem is steady state Navier-Stokes equation. And the purpose of adjont method is to obtain the gradient relationship between the cost function and the design parameters. The flow variables are expressed as velocity $\mathbf{v}$, pressure p, and design variable α and the optimization target is expressed as the minimum value of J, then the problem can be written as

$$\text{minimize} \quad J = J(\mathbf{v}, p, \alpha) \tag{1}$$

$$\text{such as} \quad R = \begin{cases} (\mathbf{v}\cdot\nabla)\mathbf{v} + \nabla p - \nabla\cdot(2\nu D(\mathbf{v})) = 0 \\ \nabla\cdot\mathbf{v} = 0 \end{cases} \tag{2}$$

with kinematic viscosity ν and the strain-rate tensor $D(\mathbf{v}) = \frac{1}{2}(\nabla\mathbf{v} + \nabla\mathbf{v}^T)$.

It is difficult to calculate the $\frac{dJ}{d\alpha}$, but it can be tackled by reformulation the cost function with Lagrange multipliers $(\mathbf{u}, q)$ as follows:

$$L = J + \int_\Omega (\mathbf{u}, q) R \, d\Omega \tag{3}$$

where R is the flow equation Eq. 3, Ω is the flow domain.

The partial derivative of L is as follows:

$$\delta L = \delta_\alpha L + \delta_\mathbf{v} L + \delta_p L \tag{4}$$

In order to get a direct relationship between L and α, the last two terms of Eq. 4 are set to zero.

$$\delta_\mathbf{v} L + \delta_p L = 0 \tag{5}$$

The integrands for $\delta\mathbf{v}$ and δp must be zero individually. After deduction, the adjoint equations are expressed as follows:

$$-2D(\mathbf{u})\mathbf{v} = -\nabla q + \nabla\cdot(2\upsilon D(\mathbf{u})) - \frac{\partial J_\Omega}{\partial \mathbf{v}} \tag{6}$$

$$\nabla\cdot\mathbf{u} = \frac{\partial J_\Omega}{\partial p}$$

The specific expressions of adjoint equations depend on the chosen cost function. As the adjoint equations are like the primal flow equation, they can use the same discrete solver. But adjoint boundary conditions need to be specified, these are

$$u_t = 0 \quad (7)$$
$$u_n = -\frac{\partial J_\Omega}{\partial p}$$
$$\mathbf{n}\cdot\nabla q = 0$$ at wall and inlet

$$q = \mathbf{u}\cdot\mathbf{v} + u_n \cdot v_n + \upsilon(n\cdot\nabla)u_n + \frac{\partial J_\Gamma}{\partial v_n} \quad (8)$$
$$0 = v_n \mathbf{u}_t + \upsilon(n\cdot\nabla)\mathbf{u}_t + \frac{\partial J_\Gamma}{\partial \mathbf{v}_t}$$ at outlet

After solving the adjoint equations for **u** and q, the sensitivities can be computed according Eq. 4

$$\frac{\partial L}{\partial \alpha_i} = \mathbf{u}_i \cdot \mathbf{v}_i V_i \quad (9)$$

2.2 RBF morphing

RBF provide a very general and flexible way of interpolation in multi-dimensional spaces, even for unstructured data where it is often impossible to apply polynomial or spline interpolation/9/. In the RBF morphing, mesh is updated by a function of motion of control points. The interpolation function $s(x)$ representing the displacement of mesh points, consists of a series of functions:

$$s(x) = \sum_{j=1}^{N_b} \gamma_j \phi(x - x_{b,j}) + q(x) \quad (10)$$

Where x is the interpolation location, x_b is the set of N_b locations carrying the data, $\emptyset(x)$ is the basis function, dependent on point distance and $q(x)$ is the polynomial function, depending on choice of basis function and γ_j.

It is needed for the consistency of interpolation that all polynomials of the order lower than $q(x)$ disappear at data points, equation is as follows:

$$\sum_{j=1}^{N_b} \gamma_j p(x_{b,j}) = 0 \quad (11)$$

The coefficients of the basis function are determined by a function,

$$\begin{bmatrix} s(x_{b,j}) \\ 0 \end{bmatrix} = \begin{bmatrix} \phi_{bb} & Q_b \\ Q_b^T & 0 \end{bmatrix} \begin{bmatrix} \gamma \\ \beta \end{bmatrix} \quad (12)$$

Where $s(xs_{b,j})$ is the function valve at interpolant locations, γ carries all γ_j coefficient and β carries all β_j coefficient, $\emptyset_{bb}$ carries the evaluation of the basis function for pairs of interpolation points, and Q_b is the rectangular matrix with $[1\ x_b]$ in each row. The Eq. 12 is difficult to solve using standard iterative techniques. A QR decomposition (direct solver) is very helpful for the computing of the dense matrix.

So, in the procedure of RBF morphing, we first establish locations of data-carrying x_b and their values, and then assemble and solve the equation set for γ and β using direct solver, finally we calculate values at desired locations by evaluating $s(x)$.

3 Valve application

In the paper, the optimization design algorithm of hydraulic components under multiple operating conditions is described by taking the optimization of valve quick-opening characteristic as an example. The valve shown in Fig.1 represents the fluid field and inlet/outlet boundaries for a typical dynamic system component. To simplify the model calculation, we created a rotational symmetry model with 5-degree angle. The resulting mesh consist of approximately 62.056 thousand primarily grid points. The flow is assumed to be incompressible and steady state with physical properties derived from water at 20 ℃.

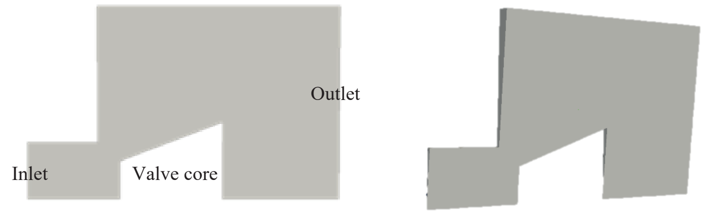

Figure 1: the model of the target valve fluid domain.

A hybrid formulation of the k-ε turbulence model is used, and constant inlet properties are set a static pressure of 1000 Pa and outlet properties are set an out pressure with 0 Pa. Velocity boundary conditions are zero-gradient everywhere except on the walls, where a fixed velocity of 0 is enforced. The solver is run initially to obtain a steady solution for the primal fluid field (1000 iterations).

4 Approach

4.1 Adjoint solver settings

We choose six different valve positions. After the mesh deformation, we get six fluid domains and perform flow field simulation for each flow field. Because the target of the study is the optimization of the control valve characteristic curve, the objective function of the adjoint solution is outlet flow rate.

$$J = \int_{\text{outlet}} v_n dA \quad (13)$$

Substituting the objective function into the adjoint boundary equation gives a specific boundary condition setting.

$$\mathbf{u}_t = 0 \quad (14)$$
$$u_n = 0$$ at wall and inlet
$$\mathbf{n}\cdot\nabla q = 0$$

$$q = \mathbf{u}\cdot\mathbf{v} + u_n \cdot v_n + \upsilon(n\cdot\nabla)u_n + 1 \quad (15)$$ at outlet
$$0 = v_n \mathbf{u}_t + \upsilon(n\cdot\nabla)\mathbf{u}_t$$

Since the sensitivity in Eq. 9 can't be calculated on the boundary due to the zero velocity on the boundary. So, we set the sensitivity on the boundary mesh cell as the data on the boundary.

4.2 Mesh morphing settings

In order to reduce the impact of mesh deformation on the calculation results, the boundary parallel to the valve core moves with the valve core. So, in the RBF morphing, motion control points are located on the valve core and parallel boundaries of it, static control points are located around the inlet and outlet and other boundaries move with deformation. The movement speed of valve is 0.02 m/s, and the valve is changed from full close to full open in 1s time. Six intermediate states are selected in the study.

In the shape optimization process, increasing the sampling rate of the control points can improve the deformation accuracy. The steepest descent method is used to transform the gradient data into control point deformation. The deformation coefficient is 1.2e-4.

5 Results

Fig 2 shows the meshes of six positions of valve. The mesh topology in the fluid domain between them does not change during motion. This reduces the effect of warping grids on the fluid calculations. In the meantime, the grid on the left side of valve core is stretched and the grid on the right is compressed.

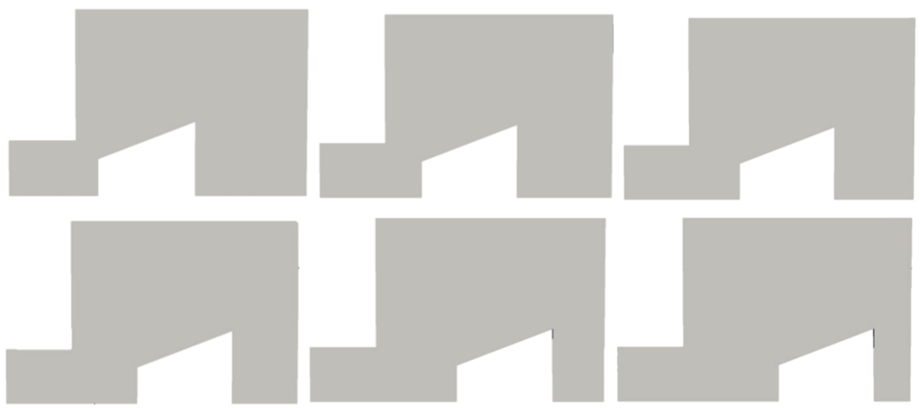

Figure 2: the models of valve core in different positions.

In the Fig 3, the sensitivity results of valve core boundary to the flow rate are shown. Positive(negative) values represent that the objective function can be reduced by displacing to the outside(inside) of the fluid field. Under each location, the influence of the boundary structure on the flow rate is different. In order to improve the quick opening characteristics of the valve, the flow rate in the middle position needs to be enlarged. From the sensitivity results, we can obtain regions that is helpful for increasing the flow rate in the opening state without affecting the flow rate in the fully open state. The sensitivity data in the opening states is screened with the sensitivity data in the fully open state (state 6). Then the sensitivity data for each state is linearly combined as the source of the overall optimization. The coefficient data can be chosen according to the different requirements of the valve. In the study, all coefficients are set 1 by default.

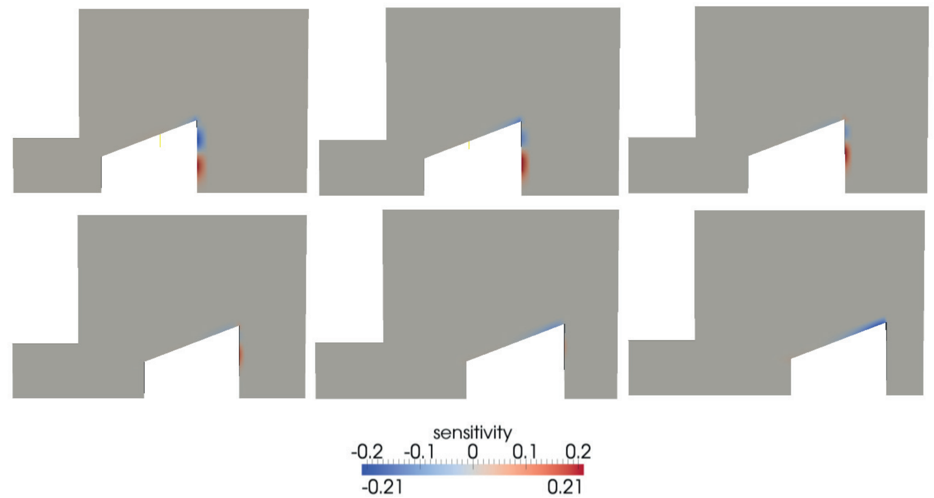

Figure 3: the sensitivity distribution of valve cores in different positions.

In the Fig 4, the deformation results of the valve core are shown.

Figure 4: the shape of optimized valve core.

In the Fig 5, the comparison chart of the flow characteristic before and after optimization are shown. The calculation results show that the optimization process helps to improve the quick opening characteristics of the valve.

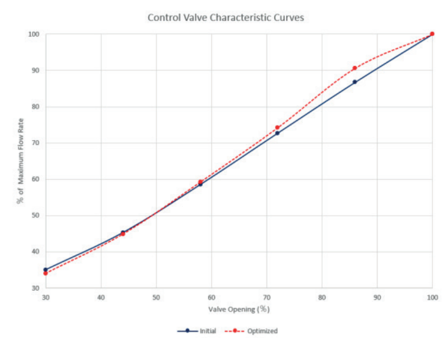

Figure 5: comparison char of valve characteristic curves.

Creating more state models can improve the accuracy of the calculation. The method is also suitable for optimizing other valve performance, such as cavitation performance.

6 Summary and Conclusion

The adjoint method is one of the fastest growing areas in CFD research and has great application prospects in the design of automated products. The calculation of the sensitivity derivatives is equivalent to the cost of the solution of the primal problem, which gives adjoint methods a huge advantage compared stochastic optimization. However, there are still many problems that need to be addressed in the practical application process. The hydraulic components not only need to meet the design requirements in the rated operating conditions, but also need to have good robustness and stability in the dynamic process /6/. The optimization under multiple operation conditions is the focus of this paper. The research presented here is based on the application of continuous adjoint of the incompressible Naiver-Stokes. In the first stage, the specific objective function is derived. After the solution of the primal and the adjoint equations, the sensitivity derivatives are calculated /7/. And then the geometric structure and mesh distribution are changed with sensitivity derivatives. Finally, after a series of iterations, the optimization model can be successfully obtained /8/. In the whole process, the most critical part is how to get relations between the design parameters and the objective function. It is very important for a comprehensive analysis of the entire optimization process that sensitivity information for each grid point can be calculated. For the multiple conditions optimization, how to build an optimal relationship under various conditions is the key issue. A simple solution is as follows, models under different operation conditions are created and calculated separately, and then the structure is improved by comparing the sensitivity of different calculation results. We have presented the theory underlying the computation of adjoint surface sensitivity and RBF morphing into the dynamic performance optimization. The application of the developed code to optimization of valve port flow characteristics demonstrated the potential of this methodology. During the optimization process, all grids are updated synchronously, and sensitivity derivatives contains the optimization information of all models. The presented method is developed in the open-source optimization tool based on OPENFOAM 2.2.

However, this method still has many problems in practical application: the adjoint solutions of some optimization objectives have very poor convergence and it is necessary to improve the calculation accuracy. After many iterative calculations, the mesh deformation causes the quality to drop, which will affect the fluid calculation. Further work is needed in excellent mesh deformation technology without affecting the calculation of flow field. In addition, for complex transient conditions optimization, selecting a reasonable multi-objective to ensure the accuracy of the calculation is of great help to the practical application of the method.

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Nomenclature

Variable	*Description*	*Unit*
p	Static Pressure	[Pa]
v	Velocity	[m/s]
$\boldsymbol{v}_t$	Tangential speed	[m/s]
v_n	Legal speed	[m/s]
V	Grid volume	[m^3]

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