Analysis of Characteristics of Damping Valve Based on High-Order Discrete Scheme

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Abstract. In this paper, based on the high-order discrete scheme, a two-way fluid-solid coupling numerical simulation is for the damping valve plate. According to the discrete method, the governing equations of fluid structure coupling of damping valve plate are studied, including the basic conservation laws; Meanwhile, it analyzes the discretization of the control equation, including the discretization method and the high-order discretization format when the finite volume method is adopted. And based on this discrete format, a numerical simulation was performed on the damping valve, the oil flow condition is analyzed, and the velocity of the throttling hole at different time points and the throttling pressure are analyzed.

Keywords. High-order discrete scheme, fluid-structure interaction, throttle slice.

1. Introduction
Damper damper plate is the most important throttling element in throttle valve system. It plays a decisive role in regulating the flow rate and direction of oil, then regulating the throttling pressure and controlling the damping force. Chen y et al. [1] Explored the equivalent thickness splitting theory of superimposed throttle disc, and carried out numerical simulation analysis based on flow theory; Based on the fluid resistance theory; Lian Z et al. [2] Analyzed the throttle disc under different disc opening, and obtained the optimized wedge throttle disc; Tezduyar T.E et al. [3] carried out fluid structure coupling analysis based on stable space-time fluid structure coupling (SSTFSI) technology, which improved the convergence of fluid structure coupling numerical simulation. In the process of two-way fluid structure coupling, the discretization of the calculation region is its core content. The discretization results have a decisive impact on the generation of dynamic structural grids, and the grid quality has an important impact on the convergence of numerical simulation results. Therefore, this paper analyzes the discretization method and discretization scheme of the calculation region, and uses the high-order discretization scheme to analyze the characteristics of the damping valve plate.

2. Two-Way Fluid-Structure Coupling Numerical Simulation Control Equation
The flow of fluid follows the laws of conservation of physics [4, 5]. The basic laws of conservation include the law of conservation of mass, momentum and energy. The governing equation is a mathematical description of the law of conservation.

2.1. Mass Conservation Equation
The outflow in the mass of the fluid micro-element in a unit time is equal to the mass of the flowing into the same time. The mass conservation equation can be derived from the law of mass conservation:
\[
\frac{\partial p}{\partial t} + \frac{\partial p u}{\partial x} + \frac{\partial p v}{\partial y} + \frac{\partial p w}{\partial z} = 0
\]

(1)

where, \( \rho \) is the density of hydraulic oil; \( t \) is the unit time; \( \mathbf{u} \) is the vector of speed.

2.2. Momentum Conservation Equation

The rate of change of momentum of a micro element with unit time is equal to the sum of all external forces acting on the micro element, and the momentum conservation equation about \( x, y, z \) three directions can be written:

\[
\frac{\partial p u}{\partial t} + \text{div}(\rho u \mathbf{u}) = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{x x}}{\partial x} + \frac{\partial \tau_{x y}}{\partial y} + \frac{\partial \tau_{x z}}{\partial z} + F_x
\]

\[
\frac{\partial p v}{\partial t} + \text{div}(\rho v \mathbf{u}) = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{y y}}{\partial y} + \frac{\partial \tau_{y z}}{\partial z} + F_y
\]

\[
\frac{\partial p w}{\partial t} + \text{div}(\rho w \mathbf{u}) = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{z z}}{\partial z} + F_z
\]

(2)

where \( p \) is the pressure, \( \tau_{x x}, \tau_{y y}, \tau_{z z} \) is the viscous stress on the surface of the infinitesimal body. \( F_x, F_y, F_z \) is the volume force. When the volume force has only gravity and only acts in the \( z \)-axis direction then \( F_x = 0, F_y = 0, F_z = -\rho g \).

2.3. Energy Conservation Equation

The law of energy conservation is the basic law of energy exchange in flow system. The theory is that the energy growth rate in a micro element is equal to its net thermal efficiency plus the work done by its volume force and area force, which can be written as:

\[
\frac{\partial (\rho T)}{\partial t} + \text{div}(\rho u T) = \text{div}(\frac{k}{c_p} \cdot \text{grad}T) + S_T
\]

(3)

where, \( c_p \) is the specific heat capacity, \( T \) is the temperature, \( k \) is the thermal conductivity, \( S_T \) is the heat generated inside the fluid and the heat energy converted by the mechanical energy of the fluid due to the viscous effect.

3. Discretization of Governing Equations

3.1. Discretization Method

There are three commonly used discretization methods in bidirectional fluid structure coupling analysis. The finite difference method divides the solution area into grid cells, uses a finite number of grid nodes instead of the solution domain, and then derives a system of difference equations containing discrete points. In the finite element method, the solution domain is arbitrarily divided into several small elements, and the interpolation function is constructed by using the extreme value principle to transform it into a finite element equation. The finite volume method divides the calculation area into structural grids, and there is a control volume integral near each structural grid node to obtain the control equation. Using the discretized control equation obtained by the finite volume method, the characteristic variables in the finite control volume have accurate integral conservation.
3.2. High-Order Discrete Scheme
When the finite volume method is used to establish the discrete equation, the field variable and its derivative value at the control volume interface can be obtained by interpolation through the corresponding value on the node. The purpose of introducing the interpolation operation is to establish a discrete equation. The interpolation method is different, and the obtained results are also different, so the interpolation method is also called discrete format. In order to improve the calculation accuracy, more relevant nodes are considered when calculating the parameter value of the control volume interface, and a higher-order interpolation formula is used for calculation, which is a higher-order discrete format.

3.2.1. Second-Order Welcome Style. In the second-order upwind style, the field variables on the control volume interface are determined by the upstream node value and the upstream far neighbor node value. The schematic diagram of the second-order welcome style is shown in figure 1.

![Figure 1. Schematic diagram of the second-order welcome style.](image)

The second-order upwind formula has second-order calculation accuracy. The discrete equation includes not only the field variables at adjacent nodes, but also the field variables at other nodes at adjacent nodes. The discrete equation is normalized by the field variable coefficients as follows:

$$a_p \phi_p = a_w \phi_w + a_{uw} \phi_{uw} + a_e \phi_e + a_{ee} \phi_{ee}$$  \hspace{1cm} (4)

where,

$$a_w = D_w + \frac{3}{2} a F_w + \frac{1}{2} a F_\tau, a_{uw} = -\frac{1}{2} a F_w, a_e = D_e - \frac{3}{2} (1- \alpha) F_\tau - \frac{1}{2} (1- \alpha) F_w$$

$$a_{ee} = \frac{1}{2} (1- \alpha) F_\tau, a_p = a_w + a_e + a_{uw} + a_{ee} + (F_e - F_w)$$.

3.2.2. QUICK Format. The QUICK format means the second-order upwind interpolation of the convection term, and it is used to calculate the second-order interpolation calculation format of the control volume interface value. The QUICK format introduces correction coefficients on the basis of linear interpolation, and uses the three node values on both sides of the control volume boundary to perform interpolation calculation. And two nodes are located on both sides of the interface, and the other node is the distant neighbor node on the windward side. After normalizing the field variable coefficients, the discrete equation is:

$$a_p \phi_p = a_w \phi_w + a_{uw} \phi_{uw} + a_e \phi_e + a_{ee} \phi_{ee}$$  \hspace{1cm} (5)

where,

$$a_w = D_w + \frac{6}{8} a F_w + \frac{1}{8} a F_\tau + \frac{3}{8} (1- \alpha) F_w, a_{uw} = -\frac{1}{8} a F_w$$

$$a_e = D_e - \frac{3}{8} a F_\tau - \frac{6}{8} (1- \alpha) F_e - \frac{1}{8} (1- \alpha) F_w, a_{ee} = \frac{1}{8} (1- \alpha) F_e$$

$$a_p = a_w + a_e + a_{uw} + a_{ee} + (F_e - F_w)$$.
4. Fluid-Solid Coupling Analysis of Damping Valve

4.1. Modeling Assumptions and Simplification

The amount of calculation for the fluid-structure coupling numerical analysis of the damping valve is huge. For this reason, assumptions and simplifications are made on the basis of ensuring the reliable analysis results.

1. The influence of temperature on the density of the oil should be ignored.
2. When the oil flows through the orifice at high speed, the heat generated by friction should be ignored.
3. The oil is assumed to be a completely incompressible liquid.

4.2. Build Fluid Model

According to the recovery valve, the numerical model of fluid field is established, as shown in figure 2. The fluid model includes an inlet, an outlet, a fluid-solid coupling surface for bidirectional data exchange, and a smooth wall without slippage. The fluid-solid coupling surface is defined as the contact point between the liquid and the damping valve plate.

Figure 2. Fluid model.

4.3. Discretization of Fluid Model of Damping Valve System

The fluid model of the damping valve system needs to be discretized. In the process of two-way fluid structure coupling numerical simulation, the damping valve plate produces large deformation. In order to improve the accuracy of numerical simulation and further enhance the convergence of the calculation process, the damping valve plate is meshed and encrypted in the Mesh module, the encryption coefficient is set to 3 times encryption, and the fluid model grid is established, as shown in figure 3.

Figure 3. Discretization model of fluid.

Check the quality of the established mesh. In the fluid structure coupling analysis, the element quality of the grid has a decisive impact on the numerical simulation results, which is related to the convergence of the numerical simulation results and the reliability of the convergence results [6, 7]. The warpage of single mesh and the orthogonality of discrete mesh are the most important. The mesh distortion mass of the fluid model is shown in figure 4, and the mesh orthogonal mass is shown in
figure 5. Warpage is one of the basic component quality inspection standards. The optimum value of warpage is zero. As can be seen from the grid warpage quality diagram in figure 4, most of the grid distortion quality of the fluid model is less than 0.3, and the grid quality is very good. For the fluid structure coupling numerical simulation analysis, the orthogonal quality of the grid should be greater than 0.1. It can be seen from figure 5 that more than 98% of the grid elements have orthogonal mass values greater than 0.1, which meets the requirements of grid warpage and grid orthogonality in fluid structure coupling numerical simulation.

4.4. Materials and Boundary Conditions
The damping characteristics of the damping valve are analyzed in the FLUENT module of ANSYS Workbench. In this paper, the density of the oil used is 890kg/m³, the kinematic viscosity is 12.2mm²/s, and the viscosity index is 202 mm²/s. The boundary condition at the inlet is 0.5m/s*t, which is set as the inlet flow velocity of oil, and the inlet velocity increases with time. The oil flow state at the outlet is set to outflow, and the liquid at the outlet is free-flowing.

4.5. Solution Strategy
In the FLUENT module, a density-based solver is used to define the solution strategy, and the solution state is defined as transient [8]. In order to accelerate the convergence of fluid structure coupling numerical simulation analysis, the relaxation factor in the iterative process is set to 0.35, the total solution time is defined as 2s, the time step is 0.05, and the total solution steps are 40.
4.6. Analysis of Numerical Simulation Results

After solving the two-way fluid-solid coupling numerical simulation, it converges after 100 iterations. The iteration convergence curve is shown in figure 6, and the force convergence curve area is shown in figure 7.

Figure 6. Iterative convergence curve.

Figure 7. Force convergence curve.

After the two-way fluid-structure coupling numerical simulation converges, the streamline diagram is shown in figure 8. From the streamline diagram, it can be seen that the speed of the oil changes suddenly when it flows through the orifice of the damping valve plate.
The flow velocity of the oil flowing through the damping valve is analyzed. The flow velocity of the oil at 0.3s, 1.0s and 2.0s is shown in Figure 9.

![Velocity streamline diagram](image)

**Figure 8** Velocity streamline diagram

It can be seen from the figure that when the oil flows through the orifice of the damping valve plate, the flow rate changes suddenly, and the flow area at the orifice has a sudden change, resulting in the throttle pressure, and with the increase of time, the oil velocity at the inlet is also keep increasing. And the maximum speed point is constantly changing, the maximum speed is 7.775m/s in 0.3s, the maximum speed is 3.664m/s in 1.0s, and the maximum speed is 7.234m/s in 2.0s. Different throttling pressures are produced due to changes in speed points. The throttling pressures at different time points are shown in Figure 10.

![Velocity diagram](image)

**Figure 9.** The velocity at (a) 0.3 s, (b) 1.0 s, (c) 2.0 s.

![Pressure diagram](image)

**Figure 10.** The pressure at (a) 0.3 s, (b) 1.0 s, (c) 2.0 s.
5. Conclusion
Based on the numerical simulation of two-way fluid-structure coupling, the paper conducts an in-depth study on the discretization of its core content calculation area. On the basis of discretization method, the finite difference method, finite element method and finite volume method are studied, and the most widely used finite volume method is fully analyzed, and the method of discretization scheme of finite volume method is proposed. Based on the method, in order to explore the flow state of oil and the throttling pressure, the two-way fluid structure coupling numerical simulation is performed on the damping valve, and it analyzes the oil flow path, the velocity characteristics of the orifice at different time points and the throttling pressure produced.

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References
[1] Chen Y, Han X, Xiang L, et al. 2020 Research on equivalent thickness of oil and gas spring damping valve IOP Conference Series: Materials Science and Engineering 926 012007.
[2] Lian Z, Meng Y, Gan L, et al. 2004 Fluid field analysis of high pressure throttle valve and its structure improvement China Petroleum Machinery.
[3] Tezduyar T E, Sathe S, Schwaab M, et al. 2010 Arterial fluid mechanics modeling with the stabilized space-time fluid-structure interaction technique International Journal for Numerical Methods in Fluids 57(5) 601-629.
[4] Bazilevs Y, Takizawa K and Tezduyar T E 2013 Computational Fluid-Structure Interaction: Methods and Applications (John Wiley & Sons Inc.).
[5] Antoci C, Gallati M and Sibilla S 2007 Numerical simulation of fluid-structure interaction by SPH Computers & Structures 85(11-14) 879-890.
[6] Gupta M and Manohar R P 2015 A critique of a second-order upwind scheme for viscous flow problems AIAA Journal 16(7) 759-761.
[7] Kurganov A, Prugger M and Wu T 2017 Second-order fully discrete central-upwind scheme for two-dimensional hyperbolic systems of conservation laws SIAM Journal on Scientific Computing 39(3) A947-A965.
[8] Cheng H M 2021 A fully local hybridised second-order accurate scheme for advection-diffusion equations (in press) https://arxiv.org/abs/2103.08551.