A Topology-alterative Algorithm for Transient Dynamic Hydraulic Response Investigation

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Abstract. In this paper, a hexahedra-based topology-alterative algorithm is proposed to simulate dynamic boundary issues of the gate opening motions in water conservancy projects. The algorithm, which cooperates with the two-phase, incompressible solver of OpenFOAM platform, enables researchers to investigate transient hydraulic characteristic variations comprehensively. Two benchmark experiments were performed to validate the numerical results under the working conditions of moving sluice gates and unsteady weir head. The time history response of water level and pressure on specified monitoring points, flow pattern scenario near moving gate, furthermore, the development of antisymmetric-revolving vertical vortices around gate piers were recorded to assess the accuracy of the proposed model. The cross-contrasting results show that the relative error of weir flow time is less than 5.00 \%. Moreover, good agreement has been obtained about time history curves of free surface elevation and pressure between numerical and experiment solutions. The vivid flow pattern shows the simulating capability of the current model and indicates an inspiring way to numerically investigate generation mechanism of vertical vortex inside gate grooves. The proposed algorithm is believed to be a useful utility on the further investigation on flow variation in real hydraulic engineering applications, such as improvement of semi-empirical discharge formulas, reduction of cavitation damage, elimination of pipe hammer pressure even spectral analysis of sluice gates with a fluid structure interaction interface.

1. Introduction
Hydraulic sluice gates are basically responsible for controlling water level and ejecting sediment, which enable hydraulic engineers to achieve various requirements, such as flood regulation, hydroelectric generation, agricultural irrigation and inland navigation. But it is more significant to understand the relationship between flow variations and gate opening before these engineering applications. Thus, a worldwide used semi-empirical technical architecture of hydraulic discharging response has been established, validated and practiced to date, based on the priori condition of a fixed rate of gate opening and a steady state assumption.

However, engineering problems and even industrial accidents have occurred because the hydrodynamic behaviour of water flow due to gate movement is not considered in the predictions. There are three primary issues that lead to economic losses for both the operation management department of the hydropower station and the water-using enterprises, i.e., accurate flux control,
cavitation damage and vortex-induced vibration. Each issue may result in negative effects on hydraulic structures and endanger citizens as well as their property.

Unfortunately, few articles of theoretical analysis and prototype or model experiments focused on transient hydraulic response investigation until computational fluid dynamics (CFD) was involved recently. Dargahi [1] captured the transient pressurized and free-surface flow features of a bottom outlet associated with a plain opening gate using volume of fluid (VOF) method implemented in Flow3D. Xiao et al. [2] conducted prototype experiments and transient simulations to predict two ski-jump jets on the flip bucket while a radial gate was closing. The motion curve of the moving boundaries surrounded by an unstructured dynamic domain was governed by a user-defined function (UDF) of ANSYS FLUENT. An identical methodology was employed to inquiry the spatial and temporal distribution law of velocity and hydrodynamic pressure, relations between weir head or angular speed of the opening radial gate and unsteady discharge coefficient [3-4].

In this paper, a novel topological-alterative two-phase flow solver embedded with a dynamic mesh class named movingDamGateTopoFvMesh is carried out based on interDyMFoam solver of OpenFOAM platform, aiming to work out problems that plain and radial gates open on settled pathway [5-6]. In comparison with commercial or proprietary CFD codes, the proposed model performs preponderantly in three aspects: (1) providing new technological support for transient working conditions analyzing; (2) adhering to the open-source general public license (GPL); (3) introducing hexahedral structured cells to improve quality and to reduce quantity of mesh lying on the dynamic domain.

2. Methodology of the topography-alterative algorithm

The topography-alterative algorithm is designed to imitate sliding gates by adding hexahedral cells (cells 10, 11, 12 and 13 in figure 1) into the computational domain. A new layer of cells is generated above the specified gate lip patch at the scheduled time step with boundary conditions and fluid flux updated in real time. The following workflow of mesh motion will be triggered if the logical switch of the algorithm is toggled to yes, otherwise, the process will be suspended.

- All the information of mesh and fluid field are stored temporarily at the current time step \( t \).
- The points lay on the gate lip patch, marked as 10, 11, 29 and 35, are about to match their inborn partners, points 13, 14, 26 and 39. New points, such as 44 and 45, will be generated to cooperate with points 20 and 33 using a self-adaptive offset matrix based on layer height \( h \) and gate thickness \( \delta \).
- A one-to-one mapping relationship is introduced to link the layer of new hexahedral elements (shadowed in figure 1a) with the original boundary cells of gate lip patch, for instance, cells 1 and 9.
- The problem of geometric closure is considered as the primary objective afterwards. Faces attached on new boundary patch, adjoined by two new cells and connected with a new cell and an original one will be produced, represented by faces (41 17 46 47), (47 46 44 45) and (33 20 11 29) in figure 1b.
- Updating mesh and zero-initializing new cells are indispensable processes before solving field information at time \( t + dt \).

3. Benchmark experiments and numerical cases

3.1. Experimental setup

Table 1 briefs the two benchmark experiments conducted to validate the proposed model using the platform shown in figure 2. A self-tapping leading screw and a reduction gearbox were introduced to manually control the opening motion of the middle plain and radial gates. Meanwhile, a digital image and pressure acquisition system was equipped to panoramically collect the water surface elevation and pressure signal in real time. The working procedures are as follows:
- Fill the upstream reservoir until the pre-determined initial weir head \( H_0 \) is reached. Then, shut down the pump.
- Initialize the digital image and pressure acquisition system.
- Open the middle gate linearly with inlet volume flow rate \( Q_{in} = 0 \, \text{m}^3\text{s}^{-1} \) until the gate opening \( e \) reaches the maximum status \( e_{\text{max}} \) and collect data within the total time \( t_{\text{tot}} \).
- Extract water level and pressure data from cameras and sensors, and identify the transition time \( t_m \) at which the flow pattern changes from orifice flow to weir-type flow, the maximum opening time \( t_{\text{max}} \).

3.2. Numerical setup
Two numerical cases are established to validate the accuracy of capturing the free surface elevation, pressure history and discharge capacity using the same configurations shown in Table 1. The transport properties applied in all cases are: air kinematic viscosity \( \nu_a = 1.0 \times 10^{-5} \, \text{m}^2\text{s}^{-1} \), air density \( \rho_a = 1.0 \, \text{kgm}^{-3} \), water kinematic viscosity \( \nu_w = 1.0 \times 10^{-6} \, \text{m}^2\text{s}^{-1} \), water density \( \rho_w = 1000 \, \text{kgm}^{-3} \), and water surface tension \( \sigma = 0.07 \, \text{kgm}^{-2} \).

![Figure 1. Sketch of a sliding gate lip patch: (a) cells and (b) faces.](image1)

| Exp. | Gate     | \( Q_{in} \) \( \text{m}^3\text{s}^{-1} \) | \( H_0 \) \( \text{m} \) | \( t_{\text{max}} \) \( \text{s} \) | \( e_{\text{max}} \) \( \text{m} \) | \( t_{\text{tot}} \) \( \text{s} \) |
|------|----------|-------------------------------|----------------|-----------------|----------------|----------------|
| 1    | Plain    | 0                             | 0.144          | 42.14           | 0.100          | 60             |
| 2    | Radial   | 0                             | 0.144          | 14.56           | 0.114          | 60             |

![Figure 2. Sketch of the digital image and pressure acquisition system containing cameras (C1) ~ (C3) and pressure sensors (S1) ~ (S10).](image2)
4. Results of experimental and numerical cases

The process at $t_m$, provided in table 2, when the gate lip patch separates entirely from the free water surface, is recorded to assess the reliability of the developed code. The relative errors of $t_m$ for both the plain and radial gate cases are less than 5.00%, which validates the performance of the proposed model.

| Gate   | $t_m$ (s) | Relative Error (%) |
|--------|-----------|--------------------|
| Plain  | 35.47     | 34.88              | -1.66            |
| Radial | 12.77     | 12.34              | -3.37            |

Figures 3 and 4 provide the time history of pressure and water level, which are used to quantitatively validate the accuracy of the proposed model via a comparison with the experimental data obtained from sensors S2, S7 and S9 and cameras C1 and C2. The left column presents the plain gate case, and the right column presents the radial gate case. The gate opening processes over time are described in the first row. In general, both figures 3 and 4 show perfect agreement between the experimental data and numerical results. This result suggests that the proposed model is accurate.

Flow patterns near the opening gate area are compared based on experimental data and numerical model results to qualitatively assess the proposed model. Figure 5 presents photographs of the free water surface in front of the gate from the view of camera C3 during the opening process for the middle plain and radial gates. Screenshots from the acquired experimental videos are shown on the left side, and the blue arrows are drawn to represent the main flow, which comes from the upstream reservoir. The locations of secondary flows are denoted by red arrowed helices. The contours of free water surfaces obtained from the numerical results are plotted on the right side for parallel comparison. Again, the experimental data and numerical model results match for both the surge in front of the gate and the secondary vortices produced.

Figure 3. The historical pressure of plain gates at the positions of sensors (a) S2, (b) S7, (c) S9, and radial gates at the positions of sensors (d) S2, (e) S7, (f) S9.
Figure 4. The historical water level under the conditions of plain gates from the view of cameras (a) C1, (b) C2, and radial gates from the view of cameras (c) C1, (d) C2.

Figure 5. Comparison of experimental and numerical results from the view of camera C3 at the opening middle plain gate when $t = 25.00$ s for (a) experiment 1, (b) case 1, and at the opening middle radial gate when $t = 9.00$ s for (c) experiment 2, (d) case 2.
5. Discussion of potential applications
The accuracy of the proposed model was tested and validated in the previous sections. The proposed model can potentially be applied in hydrodynamic studies of water flow and water conservancy projects. Two examples are illustrated in this section. The first potential application is flow velocity simulation. Traditional methods of digital imaging and monitoring merely provide coarse-scale fluid field data. Velocity measurement methods, such as laser doppler velocimetry (LDV) and particle image velocimetry (PIV), provide high resolution for a single pole or fluid domain and can be efficiently applied in bench-scale experiments. However, these measuring approaches are inferior in advising large-scale hydro-complexes for dispatching management because of their high costs and rigorous imaging conditions. However, the proposed model provides a new solution to scale and cost issues, as well as issues associated with global transient variables. The second potential application of the proposed model is flow discharge prediction. Because the numerical results discussed above are quantitatively and qualitatively consistent with the experimental data, they can be used to predict flow discharge, particularly for the case of gate opening and the associated motion.

6. Conclusions
In this paper, a domain topology-alterative, two-phase incompressible flow model is applied to simulate flow variations associated with gate opening motions in water conservancy projects. The domain topology-alterative model is formulated to simulate domain changes due to gate movement based on the OpenFOAM platform. Then, using the interDyMFoam solver, the current model is applied to simulate flow patterns of plain and radial gate opening motions at a hydropower station.

In addition, the proposed model is assessed and validated quantitatively and qualitatively based on comparisons with data obtained from two experiments in the laboratory. Good agreement was observed among the free surface elevations, pressure histories and flow patterns of the numerical results and experimental data for different scenarios. Thus, the accuracy and capability of the proposed model are illustrated.

Finally, the potential applications of the proposed model, flow velocity simulation and discharge prediction are discussed for future research. Based on the results of this study, the proposed model is considered a useful tool for investigating flow variations in real hydraulic engineering applications as well as an efficient supplement for current standards of spillway design.

References
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