Simulation of the simultaneous load rejection processes of two parallel pump turbines using a 1D–3D approach

Chengcheng Yin¹, Jiadong Yang¹, Wei Zeng¹,²*, Yongguang Cheng¹

¹, State Key Laboratory of Water Resource and Hydropower Engineering Science, Wuhan University, Wuhan 430072, China
², School of Civil, Environmental and Mining Engineering, University of Adelaide, SA 5005, Australia
w.zeng@adelaide.edu.au

Abstract A typical design scheme for pumped storage hydropower plants (PSPs) involves two or more pump turbines sharing one hydraulic and one electric unit. Load rejection is possible for a single pump turbine. It is also possible for multiple pump turbines to reject their loads simultaneously. The aim of this study is to simulate simultaneous load-rejection scenarios in PSPs using a one- and three-dimensional (1D–3D) coupling method. Here, a 1D method of characteristics (MOC) is applied to the pipeline modeling and 3D computational fluid dynamics (CFD) is applied to the turbine modeling. First, scenarios in which a pump turbine rejects its load with guide vanes stalled (or closed in 3 s) are simulated by using the 1D–3D coupling method. A comparison between the simulated results with 1D simulation and experimental results validates the coupling method. Simultaneous load rejection of two pump turbines is simulated in which only one pump turbine is modeled using 3D software. The simulated flow and head of the turbine are exchanged with the 1D pipeline model at two turbine-pipeline interfaces. Computational resources can be saved in this manner as other pump turbines are not modeled. A comparison with the 1D simulation indicates that the simplified 1D and 3D coupling methods are capable of effectively simulating the transient processes of PSPs with multiple pump turbines.

1. Introduction

The safety and operational stability of pumped storage hydropower plants (PSPs) are related to their hydraulic transient processes. Traditional methods for modeling hydraulic transient processes of PSPs include one-dimensional method of characteristics (1D MOC) [1-3], three-dimensional computational fluid dynamics (3D CFD) [4], and model experiments [5-8]. A 1D simulation applies a set of characteristic curves to model the pump turbines. However, the pump turbine characteristic curves obtained from model experiments are different from those of the prototype pump turbine due to the scale effects. Slight differences in the characteristic curves can also be observed when experiments are conducted under different water heads [9]. Furthermore, three-dimensional (3D) flow patterns such as the rotating stall, flow separation, and draft tube vortex in a pump turbine cannot be analyzed in a 1D simulation. The 3D CFD method is feasible for use in simulating the transient processes of the entire PSP system. However, considerable computational resources will be consumed.

In the 1D–3D coupling method, the pipeline system and pump turbines are modeled by the 1D and 3D CFD methods [10], respectively. Several scholars have conducted research on the 1D–3D coupling simulation method. By assuming that the pressure at the 1D–3D interaction is equal to that at the previous time step when calculating the flow, Ruprecht and Helmrich examined the water hammer in a hydropower plant that resulted from a draft tube surge [11]. Zhang et al. [12, 13] presented an explicit partly overlapped coupling (POC) method that was applied to the transient simulation of load
rejection processes of a Francis turbine. However, the aforementioned research focused on the load rejection of a single turbine, and no report on a simulation of simultaneous load rejection of multiple turbines using the 1D–3D coupling method has been reported.

To save on cost, multiple pump turbines may share a single hydraulic unit in a PSP. Compared with the load rejection of a single pump turbine, simultaneous load rejection of multiple turbines is more extreme. In this study, the 1D–3D coupling method is extended to allow simulation of the simultaneous load rejection of multiple (e.g., two) pump turbines. Only one pump turbine is modeled, and therefore the simulated data can be shared with another pump turbine. The extended method can simplify the simulation, thus saving on computational resources.

2. Model PSP

This section details the model PSP used in the numerical simulation and experiments in this study. The model PSP consists of multiple subsystems, including model units as well as piping, measurement, and power-generating systems. A schematic of the model is shown in Figure 1. Two model pump turbines, both manufactured by Harbin Electric Corporation, were installed in the model station [5]. The basic parameters of the piping system and pump turbines are given in Tables 1 and 2, respectively. The water levels in the upstream and downstream reservoirs were 14.46 and 3.76 m, respectively. Electromagnetic flow meters and pressure sensors were installed at the locations shown in Figure 1 to measure the dynamic flow $Q$ as well as the transient pressures in front of both the spiral case $H_s$ and draft tube $H_d$. Details of the transducers can be found in [5].

### Table 1. Basic parameters of the pipe system.

| Pipe section                  | Inlet | Upstream main pipe | Upstream branch pipe | Downstream main pipe | Outlet |
|-------------------------------|-------|--------------------|----------------------|----------------------|--------|
| Equivalent diameter (m)       | 0.597 | 0.357              | 0.202                | 0.300                | 0.426  |
| Length (m)                    | 2.251 | 24.154             | 2.195                | 4.891                | 16.285 |

### Table 2. Basic parameters of the model pump turbines.

| $N_Q$ (m:kW) | Inlet diameter (mm) | Outlet diameter (mm) | Guide vane height (mm) | Number of blades | Number of guide vanes | Rated $n$ (rpm) | Rated $H$ (m) | Rated $Q$ (L/s) | Rotational inertia (kg·m²) |
|--------------|---------------------|----------------------|------------------------|------------------|----------------------|-----------------|---------------|-----------------|--------------------------|
| 37.91        | 280                 | 146.34               | 24.44                  | 9                | 20                   | 1000            | 10.54         | 49.1            | 0.4125                   |

![Figure 1. Schematic of the model PSP [5].](image-url)
3. Coupling methods

The basic principles of the 1D MOC and 3D CFD coupling method are given in this section followed by a description of the extension of the coupling method to multiple turbines.

3.1 MOC method

The 1D momentum and continuity equations for transient fluid flow derived from [14] are given as:

\[ \frac{\partial Q}{\partial t} + gA \frac{\partial H}{\partial x} + \frac{f|Q|}{2DA} = 0 \]  
\[ \frac{\partial H}{\partial t} + \frac{a^2}{gA} \frac{\partial Q}{\partial x} = 0 \]

where \( x \) is the pipe length, \( t \) is the time, \( A \) is the internal cross-section area, \( D \) is the inerter diameter, \( g \) is acceleration due to gravity, \( f \) is the Darcy-Weisbach friction factor, \( H \) is the piezometric head, and \( a \) is the wave speed. This set of equations can be transformed into the following two compatibility equations, which are valid along their characteristic lines, as shown in Figure 2:

\[ C^+ : Q_p^{n+1} = C_p - C_a H_p^{n+1} \]  
\[ C^- : Q_p^{n+1} = C_n + C_a H_p^{n+1} \]

where the superscript \( n+1 \) refers to the data at the \( (n+1) \)-th time step, \( C_p \) and \( C_n \) are determined by the parameters at the \( n \)-th time step, and \( C_a = ga/A \). For an interior grid node, \( H_p^{n+1} \) and \( Q_p^{n+1} \) can be solved using (3) and (4). However, only one equation is available for a boundary node, and thus another equation must be supplemented.

3.2 One-to-one coupling

As shown in Figure 2, the \( C^- \) equation along \( R \) to \( P^{(n+1)} \) and the \( C \) equation along \( S \) to \( P^{(n+1)} \) must be developed at the coupling interface 0-0. The distributed pressure and velocity along the pipe section 1-1 in the 3D model at the \( n \)-th time step can be integrated into 1D parameters. The 1D parameters are then substituted into \( C_n \) to develop (4). Combined with (3), which can be developed directly, \( H_p^{n+1} \) and \( Q_p^{n+1} \) can be solved for this coupling interface. Details of the coupling method can be found in [12].

![Figure 2. Schematic of the partly overlapped 1D and 3D coupling [12].](image)

3.3 One-to-two coupling

Regarding PSPs with multiple pump turbines that share one main pipeline, the one-to-one coupling method is applicable to simulate the transient process only if all of the pump turbines are modeled in 3D. Considerable computational resources are consumed when using such a method.

For many PSPs, the branch pipes normally have a similar or the same size, and pump turbines of the same capacity and type are installed. Thus, an extension of the coupling method is produced by coupling one pump turbine with two sets of branches. As shown in Figure 3, only one pump turbine (#1) is modeled, and the simulation parameters can then be shared with the other visual pump turbine (#2). Similar principles can be applied to PSPs having more than two pump turbines.
4. Numerical cases

We numerically verified the model PSP using a range of load-rejection scenarios.

4.1 Modeling and simulation settings

As shown in Figure 1, the pipeline system that included the upstream main, downstream main, and branch pipes was modeled in 1D. In addition, the pump turbine along with the extended penstock in front of the spiral case, as well as the extended tailrace tunnel behind the draft tube, were all modeled using 3D Fluent. The #2 pump turbine was assumed to be closed when the single load rejection was modeled. The 3D turbine model is shown in Figure 4(a) and several monitor points are shown in Figure 4(b).

Hybrid grids were generated at different domains of the pump turbine with approximately 3.5 x 10^6 elements. Tetrahedral, wedge, and structured grids were used in the spiral case, vane diffuser, and runner and draft tube, respectively.

![Figure 4. Grid and monitor points of the 3D domain.](image)

Numerical simulations were performed using FLUENT. The compressibility of the water in a 3D domain was achieved by defining the water density function using User Defined Function [12]. The runner rotation and the movements of guide vanes were realized by using dynamic meshes. The SST k-w model was selected to model the turbulent flow with the time step set to 4 x 10^-4 s, and the convergence rate for each time step was set to 10^-5. The rotational speed during the transient process was calculated using the following rotational acceleration equation [1]:

\[ \omega^{n+1} = \omega^n + \frac{T}{J} \Delta t \]  

(5)

where \( \omega \) is the angular velocity, \( T \) is the torque, \( J \) is the rotational inertia, and \( \Delta t \) is the time step.

4.2 Single load rejection

The scenarios in which a pump turbine rejects its load with the guide vanes stalled (or closed in 3 s) were simulated using the 1D-3D coupling method. The simulated as well as measured pressure traces were filtered by a low-pass Savitzky-Golay [15] filter to extract the water-hammer pressures. The simulated results were then compared with the experimental data and 1D simulation, as shown in...
Figure 5 and Tables 3-4. The 1D simulation was performed by using the transient simulation software TOPSYS [16, 17]. Regarding the second scenario, the guide vane closed linearly within 3 s.

![Comparison of the results for the 1D–3D simulation, 1D simulation, and regular experiment for single load rejection scenarios.](image)

### Table 3. Deviation analysis for single load rejection scenarios with guide vanes stalled.

|       | $H_s$(m) | $H_d$(m) | $Q$(m³/s) | $n$(rpm) |
|-------|----------|----------|-----------|----------|
| Max   | Exp      | 14.34    | 3.55      | 0.0385   | 1345     |
|       | 1D–3D    | 14.35    | 3.73      | 0.0368   | 1386     |
|       | 1D       | 14.71    | 3.75      | 0.0378   | 1351     |
| Deviation of 1D–3D (%) | 0.09 | 1.83 | -3.54 | 3.96 |
| Deviation of 1D (%)   | 3.82 | 2.08 | -1.35 | -1.36 |
| Min   | Exp      | 11.43    | 1.68      | 0.006    | 1039     |
|       | 1D–3D    | 10.95    | 1.63      | 0.0033   | 1053     |
|       | 1D       | 11.09    | 1.9       | -0.0001  | 1011     |
| Deviation of 1D–3D (%) | -4.82 | -0.49 | -5.42 | 1.36 |
| Deviation of 1D (%)   | -3.4   | 2.32    | -12.54   | 2.66     |

### Table 4. Deviation analysis for single load rejection scenarios with guide vanes closed.

|       | $H_s$(m) | $H_d$(m) | $Q$(m³/s) | $n$(rpm) |
|-------|----------|----------|-----------|----------|
| Max   | Exp      | 15.31    | 3.82      | 0.0113   | 1351     |
|       | 1D–3D    | 15.11    | 3.38      | 0.0086   | 1375     |
|       | 1D       | 16.13    | 3.80      | 0.0105   | 1334     |
| Deviation of 1D–3D (%) | -2.01 | -4.48 | -5.48 | 2.24 |
| Deviation of 1D (%)   | 8.34   | -0.22   | -1.56    | -1.75    |
| Min   | Exp      | 11.47    | 1.22      | -0.0085  | 848      |
|       | 1D–3D    | 11.77    | 1.06      | -0.0098  | 905      |
|       | 1D       | 11.80    | 1.23      | -0.0120  | 908      |
| Deviation of 1D–3D (%) | 3.06  | -1.64   | -2.75    | 5.36     |
| Deviation of 1D (%)   | 3.42   | 0.17    | -7.22    | 5.62     |

Note: deviation = (simulation-exp)/exp₀ × 100%, where exp₀ is the initial experimental value (working head $H_s$, discharge $Q$ or rotational speed $n$).

Acceptable correlation between the results of the 1D–3D simulation and 1D simulation (or experiment) could be observed. However, differences between these plots could also be found. Apart from the simulation error of the 1D–3D simulation, the deviations could have two major explanations: 1) Characteristic curves of a larger runner having the same runner type were used in the 1D simulation. Because of the machining error and scale effects, the characteristic curves may have been slightly different when using the smaller runner in the experiments (which, however, could generate distinctive errors in transient analyses). 2) During the experiments, the model pump turbine experienced considerable vibration, particularly in the pump-turbine S-shaped region. The vibration caused fluctuated input torque and consumed energy from the water, thus affecting the entire transient process. Considering the external factors that contribute to these deviations, the 1D–3D simulation of single load rejection scenarios was validated.

### 4.3 Simultaneous load rejection
The scenarios in which two pump turbines rejected their loads simultaneously while the guide vanes simultaneously stalled (or closed in 3 s) were simulated using the 1D–3D coupling method. Because the model pump turbines in the model PSP were different, experiments with two identical pump turbines were not possible. Thus, the 1D–3D simulation results were compared only with those of the 1D simulation, as shown in Figure 6 and Tables 5-6. High correlations can be observed through this comparison, which validates the extended 1D–3D coupling transient simulation method.

![Figure 6](image-url)

(a) guide vanes stalled  
(b) guide vanes closed in 3 s

Figure 6. Comparison of the 1D–3D and 1D simulation results for the simultaneous load rejection scenarios.

| Table 5. Deviation analysis for simultaneous load rejection scenarios with guide vanes stalled. |
|---------------------------------------------------------------|
|                  | $H_h$ (m) | $H_d$ (m) | $Q$ (m³/s) | $n$ (rpm) |
| Max              | 1D–3D     | 1D        | Relative error |
|                  | 15.08     | 3.65      | -5.75       |
|                  | 15.66     | 3.75      | -0.99       |
|                  | 0.0353    | 1417      | -3.29       |
|                  | 1441      |           | 2.4         |
| Min              | 1D–3D     | 1D        | Relative error |
|                  | 10.85     | 1.3       | -1.6        |
|                  | 11.02     | 1.45      | -1.43       |
|                  | 0.0042    | 1042      | 4.9         |
|                  | 0.94      |           |             |

Note: deviation = ((1D–3D)-1D)/1D₀*100%, where 1D₀ is the initial 1D simulated value (working head $H_h$, discharge $Q$ or rotational speed $n$).

| Table 6. Deviation analysis for simultaneous load rejection scenarios with guide vanes closed. |
|---------------------------------------------------------------|
|                  | $H_h$ (m) | $H_d$ (m) | $Q$ (m³/s) | $n$ (rpm) |
| Max              | 1D–3D     | 1D        | Relative error |
|                  | 16.94     | 3.38      | -3.06       |
|                  | 17.25     | 3.49      | -1.09       |
|                  | 1440      |           | 3.68        |
| Min              | 1D–3D     | 1D        | Relative error |
|                  | 11.57     | 0.13      | -0.2        |
|                  | 11.55     | 0.5       | -3.54       |
|                  |           |           | 4.23        |

5. Conclusion

In this study, the 1D–3D coupling transient simulation method was extended to enable a transient simulation of PSPs with two or more pump turbines rejecting their loads. Only one pump turbine needed to be modeled using the 3D simulation, and the simulation parameters of the pump turbine could be shared with other pump turbines that were not modeled. Model experiments and a 1D simulation using the pump-turbine characteristic curves were conducted to validate the 1D–3D coupling method, and the extended coupling method was further validated by comparing the 1D–3D and 1D simulation results. Because only one pump turbine was simulated using the extended coupling method, computational resources could be saved, which can significantly advance the applicability of the technique to real PSPs.
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References
[1] M P, D A, P V. *Applied hydraulic transients for hydropower plants and pumping stations*. Rotterdam, The Netherlands: A. A. Balkema; 2003.
[2] Chaudhry MH. *Applied Hydraulic Transients*. New York: NY: Springer; 2014.
[3] Streeter VL, Wylie EB. *Fluid transients*. New York: McGraw-Hill; 1978.
[4] Zhang LG, Zhou DQ. CFD research on runaway transient of pumped storage power station caused by pumping power failure. *IOP Conference Series-Materials Science and Engineering*; 2013.
[5] Zeng W, Yang J, Hu J. Pumped storage system model and experimental investigations on S-induced issues during transients. *Mechanical Systems and Signal Processing*. 2017;90:350-64.
[6] Zeng W, Yang J, Guo W. Runaway Instability of Pump-Turbines in S-Shaped Regions Considering Water Compressibility. *Journal of Fluids Engineering - Transactions of the ASME*. 2015;137(0514015).
[7] Zeng W, Yang J, Hu J, Yang J. Guide-Vane Closing Schemes for Pump-Turbines Based on Transient Characteristics in S-shaped Region. *Journal of Fluids Engineering - Transactions of the ASME*. 2016;138(121102).
[8] Trivedi C, Cervantes MJ, Gandhi BK, Dahlhaug OG. Transient Pressure Measurements on a High Head Model Francis Turbine During Emergency Shutdown, Total Load Rejection, and Runaway. *Journal of Fluids Engineering - Transactions of the ASME*. 2014;136(12110712).
[9] Olimstad G, Nielsen T, Børresen B. Dependency on Runner Geometry for Reversible-Pump Turbine Characteristics in Turbine Mode of Operation. *Journal of Fluids Engineering*. 2012;134(12):121102.
[10] Wu D, Yang S, Wu P, Wang L. MOC-CFD Coupled Approach for the Analysis of the Fluid Dynamic Interaction between Water Hammer and Pump. *Journal of Hydraulic Engineering*. 2015;141(060150036).
[11] Ruprecht A, Helmrich T. Simulation of the Water Hammer in a Hydro Power Plant Caused by Draft Tube Surge. *Asme/jsme 2003 Joint Fluids Summer Engineering Conference*; 2003.
[12] Zhang X-x, Cheng Y-g. Simulation of hydraulic transients in hydropower systems using the 1-D-3-D coupling approach. *Journal of Hydrodynamics, Ser B*. 2012;24(4):595-604.
[13] Zhang X-x, Cheng Y-g, Yang J-d, Xia L-s, Lai X. Simulation of the load rejection transient process of a francis turbine by using a 1-D-3-D coupling approach. *Journal of Hydrodynamics, Ser B*. 2014;26(5):715-24.
[14] Wylie EB, Streeter VL. *Fluid Transients in Systems*. Englewood Cliffs, New Jersey, USA: Prentice Hall Inc.; 1993.
[15] Schafer R. What Is a Savitzky-Golay Filter?. *IEEE Signal Processing Magazine*. 2011;28(4):111-7.
[16] Yang JB, Yang JD, Ieee. B-Spline Surface Construction for the Complete Characteristics of Pump-Turbine. *Asia-Pacific Power and Energy Engineering Conference*. New York: Ieee; 2012.
[17] Yang W, Yang J, Guo W, Zeng W, Wang C, Saarinen L, et al. A Mathematical Model and Its Application for Hydro Power Units under Different Operating Conditions. *Energies*. 2015;8(12):10260-75.