Numerical simulation of hydraulic transients in hydropower station with complicated water conveyance system

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Abstract. With the construction of Jinping II hydropower station with extra-large diversion tunnel, Baihetan hydropower station with complicated tailwater system, Yangfanggou hydropower station with complicated surge chamber, High requirements are put forward for the calculation and analysis of hydraulic transient process. In the water transmission and power generation system design of these projects, the following technical problems was solved by Power China Huadong Engineering Corporation Limited: simulation of variable impedance coefficient of differential surge chamber, interface tracking analysis of free-surface-pressure flow system, narrow upper chamber open channel effect and simulation of trigeminy surge chamber. The solutions to those technical problems and were summarized, and the hydraulic transients simulation and calculation software of complex waterway system - Hysim was developed. Based on the field test of Jinping II Hydropower Station, Baihetan hydropower station and Yangfanggou hydropower station, the simulation calculations were carried out. The accuracy of the hydraulic transients simulation software is verified by comparing the inversion results with the test values.

1. Instruction

During the power generation of hydropower station, the guide vanes of unit open and close frequently, due to the unit load change, abnormal line and other reasons. When the opening of the guide vanes changes, the hydraulic transients occurs. Among all the hydraulic transients, the load rejection hydraulic transients is the most dangerous. When it happens, the water pressure of the pipeline increases sharply, and the unit speed rises sharply, which may lead to the rupture of the pipeline, the damage of the unit components and other accidents. In some serious cases, the safety of the whole power plant is threatened [5]. There are many accidents during the hydraulic transients in practical engineering. Therefore, in the design of water conveyance system of hydropower station, it is necessary to calculate the water pressure and unit speed under various possible conditions. This kind of calculation is called hydraulic transient calculation, which generally adopts the method of numerical simulation. Scientific and accurate simulation results of hydraulic transients also play an important role in guiding hydropower station operation and avoiding accidents.

Many subjects and fields are involved in the hydraulic transients calculation, and the calculation constraints are complex. In recent years, for the hydropower stations constructed in China, the complexity and scale of water conveyance and power generation system, and the installed capacity of the unit are increasing rapidly. Case 1: Jinping II hydropower station, 4×16.67km diversion tunnel, 4×457m³/s water flow, 8×600MW installed capacity, four giant differential surge chambers are set at the upstream side of the powerhouse, each of which is 149m high and 32.5m in diameter[3]. Case 2: Baihetan hydropower station, 16×1000MW total installed capacity, 8 giant restricted orifice surge chambers are set at the downstream side of the powerhouse, each of which is about 90m high and 48m in diameter.
Case 3: Yangfanggou hydropower station, 3×8000MW total installed capacity, 3×438m³/s water flow, huge surge chamber is set at the downstream side of the powerhouse, whose size is 25 m × 105 m. The hydraulic transients calculation of these power stations is more and more important, and of course, the accurate simulation is rarely difficult.

For the safe and stable operation of so many large and complex hydropower stations, a hydraulic transient simulation software with correct basic principle, accurate calculation results and fast calculation speed is urgently needed. Thanks to the unremitting efforts of scientific researchers and engineers, many achievements have been made in hydraulic transient simulation software, but most of them are suitable for complex pump network system, such as HAMMAER、KYPipe. Most simulation software in China’s is developed by professors in engineering colleges, which are mainly used in scientific research, rarely used in commercial applications[7].

Driven by the demand of the hydraulic transients calculation and analysis for Jinping II, Baihetan and other large and super large hydropower stations and many pumped storage hydropower stations, Huadong Engineering Corporation Limited has independently developed HYSIM (a high-precision simulation software for hydraulic transients) since 2006. In this paper, the basic principles of the software HYSIM is introduced, and the key technologies such as structural matrix method, high-precision simulation of differential surge chamber, and simulation of long and narrow upper chamber of surge chamber were described particularly. Based on the engineering examples of Jinping II, Baihetan and Yangfanggou hydropower stations, the accuracy of simulation of was shown.

2. Key Technologies of HYSIM

2.1. Basic equations of hydraulic transients

In the hydraulic transient calculation, from the continuity equation and dynamic equation of water flow, the basic equations can be deduced as follows[1]:

\[ \frac{Q}{A} \frac{\partial H}{\partial t} + \frac{\partial H}{\partial x} + \frac{a^2}{gA} \frac{\partial Q}{\partial x} - \frac{Q}{A} \sin \beta = 0 \]  
\[ g \frac{\partial H}{\partial x} + \frac{Q}{A^2} \frac{\partial Q}{\partial x} = \frac{1}{A} \frac{\partial Q}{\partial t} + \frac{fO[Q]}{2DA^2} = 0 \]  

Where \( Q \) and \( H \) are the discharge and head in the pipe respectively; \( A \) is the cross-sectional area of the pipe; \( x \) is the distance along the pipe; \( t \) is the time; \( a \) is the wave velocity of water hammer; \( g \) is the gravitational acceleration; \( \beta \) is the longitudinal slope of the pipe; \( f \) is the friction coefficient; \( D \) is the pipe diameter.

Leaving out minor items in the basic equations, hyperbolic partial differential equations are obtained, which can be transformed into ordinary differential equations by means of characteristic method. With boundary conditions and initial conditions, pressure and flow during the whole transient process in the pressure conduit can be calculated.

2.2. Structural matrix method

The structural matrix method is adopted in the simulation software HYSIM. The method uses the rigid matrix model to establish a mathematical model of a complex pressurized waterway system, as shown in Figure 1. Since the rigid matrix method used in structural analysis is only applicable to analytical calculations in the linear range, the structural matrix method of the earliest waterway systems is only used for small fluctuation analysis calculations of hydropower station systems. In 1993, the method was extended to the mathematical model of large fluctuations in hydropower systems. Compared with the feature line method, the structural matrix method has the advantages of easier programming and easier modularization [2].
The calculation steps of the hydraulic transients calculation are shown in Figure 2.

The structural matrix method has the advantages of fast calculation speed and high accuracy, compared with method of characteristic. For most general algorithm, the solution method of equations is based on the balance equations of loop head pressure and continuous equations of node flow. For the structural matrix method, complex system is decomposed into simple problems and the whole system matrix to express the element mathematical model can be established. Therefore, programming is more convenient, modularization is easier to realize and the secondary development is convenient.

2.3. Hydraulic transient simulation of differential surge chamber

There are many kinds of surge chamber, such as simple surge chamber, restricted orifice surge chamber, air cushion surge chamber, and differential surge chamber and so on. The flow pattern of simple surge chamber and restricted orifice surge chamber is relatively simple, and the simulation calculation is relatively simple. The flow state of differential surge chamber is complex due to the complex structure, and the simulation is difficult. The differential surge chamber is composed of a large well (usually one) and riser wells (which can be multiple). It can be divided into two types according to whether the bottom of the well is connected with the riser well. The one that the bottom is not connected called impedance hole type and the one that the bottom is connected is called backflow hole type, as shown in Figure 3.
For the impedance hole type, the inlet and outlet of the wells are independent of each other. So the wells can be treated as independent surge chambers in the simulation calculation. For the backflow hole type, the flow pattern in the bottom hole is much more complex, and the hole impedance coefficient is different from that of restricted orifice surge chamber obviously. The impedance coefficient of the backflow hole and riser bottom hole is a dynamic coefficient, and the value depends on the flow rate ratio and the flow direction in the holes. To improve the simulation accuracy, the relationship among the impedance coefficient, flow proportion and flow direction is defined as function curve in the simulation software. The Equations is:

\[
I \frac{dQ_s}{dt} + H_m - H_L + kQ_s |Q_s| = 0
\]

(3)

\[
I = \sum_{i=1}^{n} \frac{L_i}{8A_i}
\]

(4)

\[
k = (k_i + \sum_{i=1}^{n} \beta_i)
\]

(5)

where \( t \) is time; \( Q_s \) is the outflow rate of surge chamber; \( H_m \) is the head at joint of surge chamber and channel; \( H_L \) is the water surface elevation of surge chamber; \( k \) is the impedance coefficient of impedance hole; \( L_i, A_i \) and \( \beta_i \) are the length, horizontal section area and head loss coefficient of surge chamber per section respectively.

2.4. Hydraulic transient simulation of long and narrow upper chamber

The flow phenomena exists in the long and narrow upper chamber of surge chamber, as shown in Figure 4. The characteristic method and Preissmann four-point difference method are commonly used for numerical calculation of unsteady flow in channels [5]. When the characteristic line method is used, the time step should be very small due to the restriction of the so called Courant-Friederichs-Levy condition, so the calculation speed is certainly very slow. However, the Preissmann four-point difference method is unconditionally converging, so a larger time step can be selected. The calculation speed is very fast, so it is used widely [6].
The schematic diagram of the Preissmann four-point difference method is shown in Figure 5. The feature of this difference method is to take the partial derivative of the dependent variable around the M point in the rectangular grid for difference quotient approximation.

Let the function \( f(x, t) \) in each grid changing in a straight line. The function values of the four points L, R, U, and D on the grid should be represented by the values of nodes a, b, c, and d:

\[
\begin{align*}
    f_L &= \alpha f_{m+1}^{t+\Delta t} + (1-\alpha) f_m^t \\
    f_R &= \alpha f_{m+1}^{t+\Delta t} + (1-\alpha) f_{m+1}^t \\
    f_U &= 0.5(f_m^t + f_{m+1}^{t+\Delta t}) \\
    f_D &= 0.5(f_m^t + f_{m+1}^{t+\Delta t})
\end{align*}
\]

The differential quotient approximation formula for the partial derivative of the M point is:

\[
\left. \frac{\partial f}{\partial x} \right|_{M} \approx \frac{f_R - f_L}{\Delta x_m} = \frac{f_{m+1}^{t+\Delta t} - f_{m}^{t+\Delta t}}{\Delta x_m} + (1-\alpha) \frac{f_{m+1}^t - f_m^t}{\Delta x_m} \\
\left. \frac{\partial f}{\partial t} \right|_{M} \approx \frac{f_U - f_D}{\Delta t} = \frac{f_{m+1}^{t+\Delta t} - f_{m+1}^{t+\Delta t} + f_m^{t+\Delta t} - f_m^t}{2\Delta t}
\]

If the coefficient term and the non-derivative term in the Saint-Venant equations are also denoted by
f, then the value of f is calculated using the M point value, which is:

\[ f_M = \frac{\alpha}{2} (f_{m+1} + f_{m+1}) + \frac{(1-\alpha)}{2} (f_{m+1} + f_{m+1}) \]  

(12)

2.5. Hydraulic transient simulation of trigeminy surge chamber

For the hydropower station in which multi-machine shared one tail water tunnel, the impedance hole of the surge chamber is often placed on the branch pipe, and then through the connecting pipe, multiple units share a large room. The typical layout three-throttled-orifice surge chamber (which is also called as trigeminy surge chamber) is shown in Figure 6.

Compared with common surge chamber, the numerical simulation of the multi-throttled-orifice surge chamber is difficult. The main difficulty is in the determination of the initial steady state. Taking three-throttled-orifice surge chamber as an example, in the initial steady state, the head loss of each branch pipe may be different, and the impedance coefficients of the three impedance orifices may not be exactly the same, and the water flow in and out of the impedance orifice must be present. To calculate the flow accurately is the focus and difficulty [9].

![Figure 6. Calculation diagram of trigeminy surge chamber](image)

The structural matrix of three-throttled-orifice surge chamber is more complicated, but the basic principle is also based on the concept of hydraulic impedance. In addition, in the specific treatment, three-throttled-orifice surge chamber also is a simpler than the single pressure surge chamber: the sectional size of the ordinary pressure surge chamber is often small, so it is necessary to calculate the inertia of the indoor water and the water in the transients calculation and to consider the damping effect and other factors of the well; while three-throttled-orifice surge chamber has a large horizontal section, the water level changes slowly during the hydraulic transients, and the indoor flow velocity is extremely small. Considering the indoor flow velocity, there is not much engineering significance, so the inertia and damping effect of the chamber wall can be ignored. Therefore, the hydraulic impedance of the three-throttled-orifice surge chamber is mainly the hydraulic impedance of the three impedance ports.

According to the above analysis, the mathematical model of three-throttled-orifice surge chamber is:

\[ H_4 - H_1 = k_1 |Q_4|Q_1 \]  

(13)

\[ H_4 - H_2 = k_2 |Q_4|Q_2 \]  

(14)

\[ H_4 - H_3 = k_3 |Q_4|Q_3 \]  

(15)

\[ A \frac{dH_4}{dt} = -Q_4 = -(Q_4 + Q_2 + Q_3) \]  

(16)

Where: \( H_1, H_2, \) and \( H_3 \) are the heads of the three impedance orifices and the pipe joints; \( Q_1, Q_2, \) and \( Q_3 \) are the flow points of the three impedance orifices and the pipe joint; \( H_4 \) is the head of the pressure surge chamber; \( Q_4 \) is the flow in the chamber; \( k_1, k_2, \) and \( k_3 \) are the impedance coefficients of the three impedance
orifices; \( A \) is the cross-sectional area of the surge chamber.

3. Analysis of Engineering Examples

3.1. Jinping II Hydropower Station - Long Water Diversion System

Jinping II hydropower station is the world's largest power station under construction in aspect of hydraulic tunnels and surge chambers [8], which has the largest group of hydraulic tunnels, including 4×16.67km diversion tunnel and four large differential surge chambers which is 149m high and 32.5m in diameter. The water conveyance system of Jinping II hydropower station is shown in Figure 7.

![Figure 7. Schematic diagram of water conveyance system for Jinping II hydropower station](image)

3.1.1. Selection of Surge Chambers. Because of the long diversion tunnel (17km) and large diversion flow (457.2m³/s), it is necessary to select the one with good hydraulics conditions, low construction difficulty and low project investment. Comparisons are made between different types of surge chambers. The selectable types are restricted orifice surge chamber and differential surge chamber. In the preliminary calculation by theoretical formula, the restricted orifice surge chamber is better in terms of the maximum pressure difference of the bottom plate, project investment and construction difficulty, while the differential surge chamber is better in terms of the surge attenuation rate and the minimum pressure at draft tube inlet. It seems that the throttled chamber is better on the whole. However, there are still some unsatisfactory aspects for restricted orifice surge chamber. First, the wave fluctuation attenuation in the surge chamber is too slow during the transient process. Second, the minimum surge is below the limited depth after load rejection, so it is the necessary to set up operating restrictions for the units.

![Figure 8. Comparison of water level fluctuations of different surge chambers](image)

Therefore, it is necessary to carry out hydraulic calculation and analyses on the throttled and differential type surge chamber. The water level fluctuation of two surge chambers after the load rejection is shown in Figure 8. It can be seen that the maximum surge level in the differential surge chamber is lower than that in the restricted orifice surge chamber, the water level fluctuation attenuation in the differential surge chamber is faster than that in the restricted orifice surge chamber. In aspects of controlling the maximum and minimum surge level, accelerating the attenuation of surges and improving the operating
conditions of the unit, the differential surge chamber was finally adopted.

3.1.2. Field Test and Inversion Calculation. In December 2012, load rejection tests of unit 1 and 2 were carried out in No.1 diversion system in Jinping (the unit with 25%, 50%, 75% and 100% rated load); Inversion calculations were carried out by the software HYSIM according to the water level, flow rate, unit output and other conditions. The test values and inversion calculation results of double units 100% load rejection are shown in Table 1 and Figure 9-10.

Table 1. Comparison of test values and calculation results.

| Key parameter                     | Unit 1     | Unit 2     |
|-----------------------------------|------------|------------|
| Maximum spiral case pressure (m) | Calculation result 368.3 | Calculation result 368.2 |
|                                   | Test value 365.9 | Test value 365.5 |
| Maximum unit speed rise rate (%)  | Calculation result 40.6 | Calculation result 40.6 |
|                                   | Test value 39.8 | Test value 39.9 |
| Maximum surge level (m)           | Calculation result 1681.4 | Calculation result 1681.0 |
|                                   | Test value 1681.0 | Test value 1681.0 |
| Minimum surge level (m)           | Calculation result 1603.5 | Calculation result 1603.9 |
|                                   | Test value 1603.9 | Test value 1603.9 |
| Total surge amplitude (m)         | Calculation result 77.9 | Calculation result 77.9 |
|                                   | Test value 77.1 | Test value 77.1 |

Figure 9. Spiral case pressure of unit 1
Figure 10. Surge level in the chamber

It can be seen that the inversion calculation results are in good agreement with the field test values. The calculation error of the pressure in spiral case, and the water level in the surge chamber are all within 5%. The reliability of the simulation software HYSIM are verified.

3.2. Baihetan Hydropower Station - Complex Tailrace System
The total installed capacity of Baihetan Hydropower Station is 16,000 MW. Eight 1000 MW Francis turbine and four giant throttled tailrace surge chambers are arranged on the left and right banks respectively. The water conveyance system is shown in Figure 11.
3.2.1. Long and Narrow Upper Chamber. In order to limit the maximum surge level in the surge chamber, the surge chamber with long and narrow upper chamber is designed in Baihetan hydropower station, so the simulation of the surge in upper chamber is involved in the simulation calculation of the hydraulic transient process. In the general simplified calculation, the channel effect of the long and narrow upper chamber was neglected, and the narrow channel upper chamber was simplified into the circular section upper chamber. This simplification facilitates the calculation of the transient process at the expense of simulation precision. In order to reflect the water flow state in the long and narrow upper chamber and the influence on the surge level of the surge chamber more realistically, the simulation model of the channel upper chamber was used in the transient process calculation.

3.2.2. Selection of Surge Chambers. The transient process under the selected working conditions were calculated. The calculation results and the comparative analysis of the two models are shown in Figure 12.

![Figure 12. Surge level in the chamber](image)

It can be seen that the channel effect of the upper chamber has a great influence on the transient process. When the channel effect is considered, the maximum water level in the upper chamber is smaller, the minimum water level is greater, and the surge attenuation rate is much faster. The reason is that the open channel effect is equivalent to adding a damping effect to the surge.

The water depth changing with time at the inlet and the middle of the upper chamber are shown in Figure 13. It can be seen that the fluctuation in the upper chamber decays very quickly. For long and narrow upper chamber, the fluctuation process of the water level has the same periodicity as the surge chamber. That is, the processes of filling and draining happened in one cycle.

3.3. Yangfanggou hydropower station - complex surge chamber
Yangfanggou hydropower station is equipped with three 800 MW Francis turbines with a total installed capacity of 2,400 MW and a rated flow of turbines of 437.9 m³/s. The power station diversion tunnel adopts single-machine and single-hole water supply, and the tail water system adopts a layout scheme in which three units share one tail water hole. A long corridor-shaped impedance tail water surge chamber is arranged on the tail water support hole. The distance between the tail water surge chamber and the plant center line is
150.0 m. The surge chamber size is 25 m × 105 m, and the lower part of the surge chamber is divided into three chambers by the partition wall, and the upstream side of the pressure surge chamber is provided with a tail pipe maintenance gate. The tail water conveyance system is shown in Figure 14.

**Figure 14.** Schematic diagram of tail water conveyance system for Yangfanggou hydropower station

### 3.3.1. Hydraulic transients simulation of trigeminy surge chamber

In general, the calculation is to simplify the process: the multiple impedance holes are combined and placed in the position of the manifold, and the inertia of the water in the pressure surge chamber and the friction between the well wall and the water are not considered.

According to the static and dynamic models of the three-throttled-orifice surge chamber, the two impedance holes are combined and placed in the manifold position and three-throttled-orifice surge chamber, that is, the large fluctuation transient process of the simplified model and the triple model. The simplified principle is that the area of the single impedance hole in the simplified model is equal to the sum of the three impedance areas in the three-throttled-orifice surge chamber.

**Figure 15.** Pressure in the spiral case and draft tube versus time

It can be seen from the results that for the calculation of the large fluctuation transient process of three-throttled-orifice surge chamber, the simplified treatment method of combining the impedance orifices is compared with the actual situation treatment method, the maximum pressure at the end of the volute and the maximum speed of the unit increase rate change small. This is because the maximum speed rise rate of the unit is less affected by the surge chamber, and the surge chamber is placed above the tail water system, which does not adjust the pressure at the end of the volute, so the maximum pressure at the end of the volute and the maximum speed of the unit change small. However, for the minimum pressure of the draft tube inlet, the calculation results of the two models differ greatly.

For the calculation of the large wave transient process of three-throttled-orifice surge chamber hydropower station, when the simplified model of combining the impedance orifices was compared with the triple model of the actual situation, the initial value of the tail water inlet pressure is no difference, but the difference during the transient process is large. Specifically, before the vanes are completely closed, the pressure drop of the draft tube inlet of the triple model is smaller than that of the simplified model, indicating that the water hammer reflection effect is better; after the vanes are completely closed,
the pressure values of the draft tube inlets of the two models changed small, and it was expressed as a
cyclical change with the fluctuation of the water level in the surge chamber. For the minimum pressure
of the draft tube inlet, the results of the simplified model calculation are more dangerous than the triple
model.

In summary, compared with the simulation results of the simplified model's load rejection process,
the triple model can more accurately reflect the flow state at the bottom of the surge chamber in the
steady condition, and more realistically reflect the change of the tail water pressure during the transition.
Specifically, if only the water level change of the surge chamber is considered, the simplified model is
consistent with the calculation result of the triple model as long as the impedance orifice area is con-
sistent. However, for the tail water inlet pressure, the calculation result of the simplified model is not
reliable, and the triple model is closer to the true value.

4. Conclusions
In this paper, several key simulation technologies of the hydraulic transients were introduced in detail: simulation of variable impedance coefficient of differential surge chamber, interface tracking analysis of free-surface-pressure flow system, narrow upper chamber open channel effect and simulation of tri-
geominy surge chamber. Based on three engineering examples, the application of the simulation software
HYSIM was showed. The following conclusions can be drawn.

(1) The high precision simulation technology of differential surge chamber provides a basis for the
type selection of surge chamber. Through comparison, the differential surge chamber was finally chosen
in Jinping II hydropower station, which can control the maximum and minimum surge level and accel-
erate the attenuation of surges.

(2) For the surge chamber with long and narrow upper chamber, the channel effect should not be
ignored. When it is considered, the maximum surge level is smaller, the minimum surge level is greater,
and the surge attenuation rate is much faster.

(3) For the trigeminy surge chamber, the triple model can more realistically reflecting the change of
the tail water pressure during the transition.

References
[1] Adamkowski, A. 2001. Case Study: Lapino Powerplant Penstock Failure. Journal of Hydraulic
Engineering 127(7): 547-555.
[2] Brekke, H. and Li, X.X. 1988. A New Approach to the Mathematical Modelling of Hydropower
Systems. London: Conference of CONTROL 88.
[3] Chen, X.R. & Fan, L. Ju, X.M. 2007. Hydraulic research and design optimization of the diversion
system at Jinping hydropower station. Dam & Safety 3:1-7.
[4] Chen, Y.Q. & Hu, W.M. & Zou, Z.B. 2011. New research development of 1000MW hydro-
generator units. Electric Power construction 32(6):62-66.
[5] Kahawita, R. 2013. Applied Hydraulic Transient. Berlin: Springer.
[6] Martin, C.S. & Defazio, F.G. 1969. Open-channel surge simulation by digital computer. Journal
of the Hydraulics Division 95:2049-2070.
[7] Liu, G.G. & Chen Y.C. & Wang J.F. 2014. Software development and application of transients
calculation in hydraulic generating units based on MATLAB. China Rural Water and Hydro-
power 2014(5):150-154
[8] Wu S.Y. & Wang G. & Xu J.S. 2008. Research on TBM type-selection and key construction
technology for JINPING II hydropower station. Chinese Journal of Rock Mechanics and Engi-
neering 27(10):2000-2009.
[9] YU Xiaodong, ZHANG Jian, CHEN Sheng. Hydraulic transients in hydropower station with bi-
furcated pipes converging behind tailrace surge tank [J]. Journal of Hydroelectric Engineering,
2014, 33(6): 142-148.