Research and Application on Numerical Simulation of Hydraulic Transients in Complex Water Conveyance System

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Abstract. Accurate simulation of hydraulic transients is crucial and complicated in the design of hydropower station and pumped storage power station. In this paper, key technologies for hydraulic transient simulation calculation in complex water conveyance system were studied. The structural matrix method with advantages of high accuracy and fast speed for numerical calculation was introduced. Complicated elements in the conveyance system were refined, such as high precision simulation of differential surge chamber, simulation of long and narrow upper chamber, new interpolation method for characteristic curve of pumped storage unit. Based on Jinping II hydropower station with special long headrace system and differential surge chamber, Baihetan hydropower station with complex tailrace system and large surge chamber and Xianyou pumped storage power station with complex unit characteristics and various working conditions, the application of the simulation software HYSIM in field test and inversion calculation was illustrated. The paper providing references for the design of similar projects.

1. Instruction
Due to line fault, circuit breaker trip and other reasons, load rejection transition process occurs in hydropower stations and pumped storage power stations frequently. When it happens, the water pressure in the water conveyance system increases sharply and the unit speed increases greatly, which may lead to pressure pipeline rupture, unit component damage and other accidents. In serious case, the safety of the whole power station is threatened [1]. Therefore, in the design of the station’s water conveyance system, transition process calculation and analysis under various possible conditions is a very necessary task. Scientific and accurate calculation results and analysis play an important role in guiding operation and avoiding accidents [2].

The calculation and analysis of hydraulic transient involves many disciplines in different fields and the boundary conditions are very complex. Due to the increasing complexity and scale of the water conveyance and water generation system (Jinping II hydropower station, 16.67km diversion tunnel, 457m^3/s flow, 149m tall differential surge chamber [3]), the increasing installed capacity of the unit (Baihetan hydropower station, 1000MW single unit capacity, 16000MW total installed capacity [4]), the difficulty in studying the hydraulic transition process in these stations is increasing obviously. In addition, for pumped storage power stations, the unique reversible turbine and complex operating conditions make the hydraulic transition process calculation and analysis particularly complex (The turbine is used for both generating power and pumping water, the working condition switches quickly, the unit starts up and shuts down frequently, the pressure pulsates violently [5]).

A hydraulic transient simulation software with correct mathematical model, accurate calculation method, high calculation speed and suitable for complex operating conditions certainly have vital engineering application value. In the development of hydraulic transient simulation software, many
achievements have been made, but most of them are suitable for complex pump network system, such as HAMMAER, HYTRAN, PIPENET. The simulation software in China are mostly developed in science and engineering universities, which are mainly for self-use, with little information disclosed [6]. In this paper, the principle and application of HYSIM, a high-precision simulation software for hydraulic transition process, is introduced. The key technologies such as structural matrix method, high-precision simulation of differential surge chamber, simulation of long and narrow upper chamber of surge chamber, and new interpolation method for characteristic curve of pumped storage unit were described particularly. Based on three engineering examples, the importance of simulation analysis of hydraulic transition process in the design of hydropower station and pumped storage power station was shown.

2. Key Technologies of HYSIM

2.1. Basic Principle of Structural Matrix Method

The structural matrix method is adopted in the simulation software HYSIM. This method makes use of the same characteristics of pressure and flow \((H, Q)\) in the pressurized waterway system as the stress and displacement \((F, S)\) in the structure girder frame [7]. The rigid matrix model building method used in structural analysis is applied to the mathematical model building of complex pressurized waterway system.

In addition to high precision, the structural matrix method has many other advantages. 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. Therefore, the modularity of the software is low and the secondary development is inconvenient. However, it is easy for the structural matrix method to realize modularity and secondary development. Besides, the idea of zero node flow is used to construct diagonal sparse matrix in structural matrix method, and the methods of matrix dimension reduction and automatic step changing were applied to solve the system matrix. As a result, the calculation speed is faster.

2.2. High Precision Simulation of Differential Surge Chamber

The differential surge chamber is composed of large well and riser well. According to whether the bottom of large wells and riser wells are connected or not, it can be divided into two types. 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.

For the former, the inlet and outlet of the large well and the riser well are independent of each other. When the water level in the large well and riser well below the overflow elevation, the two wells can be treated as two independent surge chambers. For the latter, the flow pattern in the backflow hole and riser well bottom hole is very complicated, and the hole impedance coefficient is different from that of conventional throttled surge chamber obviously. The impedance coefficient of the backflow hole and riser well bottom hole is not constant, but closely related to the flow pattern in the two holes. Because its impedance characteristics have a strong functional correlation with the proportion of flow in the backflow hole and the bottom hole of the riser well, it was defined as a function curve in the simulation software to improve the simulation accuracy. The Equations of motion is:

\[ I \frac{dQ}{dt} + H_m - H_L + kQ_s |Q_s| = 0 \]  
\[ I = \sum_{i=1}^{n} \frac{L_i}{gA_i} \]  
\[ k = (k_s + \sum_{i=1}^{n} \beta_i) \]

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; $k_s$ 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;

2.3. Simulation of Long and Narrow Upper Chamber
In hydropower stations and pump stations, there are many unsteady flow phenomena in headrace channels, tailrace channels and unpressurized tunnels. In addition, it also exists in the long and narrow upper chamber of surge chamber, as shown in figure 1. The characteristic method and Preissmann four-point difference method are commonly used for numerical calculation of unsteady flow in channels [8]. 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 the restriction of the Courant-Friederichs-Levy condition is vanished. As a result, a larger time step can be selected to speed up the calculation speed, so it is used widely [1].

![Figure 1. Long and narrow upper chamber](image1)

![Figure 2. Preissmann difference method format.](image2)

The schematic diagram of the Preissmann four-point difference method is shown in figure 2. 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. The distance step of grid can be unequal, while the time step is generally equal. In aspect of time, the distance between M point and known time layer N is $\alpha \Delta t$, and the distance from unknown time layer $n+1$ is $(1-\alpha) \Delta t$. $\alpha$ is the weighting coefficient, ranging from 0 to 1. The greater the $\alpha$, the lower the calculation accuracy and the higher the stability. A better result can be obtained by taking 0.6 of $\alpha$.

The implicit difference scheme can be formed by bringing the above formulas into Saint-Venant equations. For the channel with N cross sections, there are 2N unknowns in total. There are $(N-1)$ grids in the whole channel section, so $2(N-1)$ difference equations can be built. Together with the 2 boundary condition equations provided by the upper and lower boundary, the total number of equations is 2N. All unknowns can be solved.

2.4. New Interpolation Technology of Pumping Turbine Characteristic Curve
The pump turbine is a variant of the francis turbine to a large extent, but in terms of hydraulic characteristics, the two turbines have considerable differences. The most obvious difference is that there is an unstable region on the pump turbine characteristic curve, namely S region [9]. In the calculation of the transition process, interpolation between equal-opening curves is necessary to find the operating conditions of the turbine. For Francis turbines, satisfied results can be obtained by longitudinal interpolation method. However, for pump turbines, serious interpolation distortion will be caused by the longitudinal interpolation method, because of the multi-value of S region, the perpendicularity and the reverse of the curve.

Orthogonal interpolation is a good solution to solve this problem. When the orthogonal interpola-
tion method is used, transformation of the curve is unnecessary, and the programming is relatively simple. Compared with the simple vertical interpolation or horizontal interpolation, however, the calculation steps are much longer. In the process of iterative computation, orthogonal interpolation method is obviously disadvantageous in terms of the rapidity of computation. Since the S region only occupies a small area of the entire characteristic curve, orthogonal interpolation is used only in the region where it is necessary, longitudinal interpolation is used in the region where the curve is very flat, and transverse interpolation is used in the region where the curve is very steep, as shown in figure 3. As a result, the interpolation speed is significantly improved. This new interpolation method is also called the combined interpolation method. The key point of this method is to partition the characteristic curve to decide which interpolation method to use. Conveniently, it is unnecessary to make partition in advance, but just to make a simple judgment on the slope of two small local curves at the beginning of iteration.

![Figure 3. Schematic diagram of combined interpolation.](image)

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 [10]., which has the largest group of hydraulic tunnels, including four 17km water conveyance tunnels and four large differential surge chambers.

3.1.1. Selection of Surge Chambers. Because of the long diversion tunnel (17km), large diversion flow (457.2m³/s), and high flow velocity (4.04m/s), it is necessary to compare different types of surge chambers, and select the one with good hydraulics conditions, low construction difficulty and low project investment. The selectable types are throttled surge chamber and differential surge chamber. In the preliminary calculation by theoretical formula, the throttled 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 throttled surge chamber. First, the wave fluctuation attenuation in the surge chamber is too slow during the transition 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.
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 4. It can be seen that the maximum surge level in the differential surge chamber is lower than that in the impedance surge chamber, the water level fluctuation attenuation in the differential surge chamber is faster than that in the throttled 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); at the same time of the test, 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.

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

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.
3.2.1. Long and Narrow Upper Chamber. In order to limit the maximum surge level in the surge chamber, Baihetan hydropower station adopts a surge chamber with long and narrow upper chamber, so the simulation of the surge in upper chamber is involved in the simulation calculation of the hydraulic transition 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 transition 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 transition process calculation.

3.2.2. Selection of Surge Chambers. The transition process under the selected working conditions were calculated. The calculation results and the comparative analysis of the two models are shown in figure 5.

![Figure 5. Surge level in the chamber.](image1)

![Figure 6. Water depth in the surge chamber.](image2)

It can be seen that the channel effect of the upper chamber has a great influence on the transition 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 6. 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. Xianyou Pump Storage Power Station- Reversible Turbine

The Xianyou pump storage power station has four 300 MW reversible pump turbines, whose total installed capacity is 1200 MW. The whole water conveyance system is 2061.8 m in length.

In order to ensure safe operation of the pumped storage power station, series of field tests such as load rejection, pump power off, and hydraulic disturbance must be carried out before the power station is put into production. At the same time of the field test, the inversion calculation and analysis of the transition process was carried out. The boundary condition in the simulation was exactly the same as that in the field test. The turbine flow, pipe pressure and gate opening in the initial state were calculated by upstream water level, downstream water level and unit output in the field tests. With the same closing law, the load rejection transient process was calculated by simulation software. By inversion calculation, the accuracy of the simulation software is verified, and the extreme conditions can be predicted.

The closing law of the pump turbine in this station is: the wicket gate blocked in the initial position for 10s and then shut down with one straight line for 25s. It is found that the fluctuating pressure is larger when the wicket gate is blocked and relatively small when the wicket gate is closing. So, the
load rejection process is divided into two periods. The former is blocked period and the latter is closing period.

3.3.1. Comparison under Double Units Load Rejection. In March 2013, load rejection tests of unit 1 and 2 were carried out in No.1 diversion system in Xianyou (the unit with 25%, 50%, 75% and 100% rated load); In the same boundary, the filed test values and numerical calculation results under condition of double units load rejection are shown in figures 7–8.

![Figure 7. Spiral case pressure of disturbed unit.](image1)

![Figure 8. Relative speed of the disturbed unit.](image2)

It can be seen that without considering pressure pulsation, the numerical calculation results is in good agreement with the test values, which verifies the reliability of the transition process simulation software HYSIM. The numerical calculation results can be used to predict extreme load rejection conditions.

3.3.2. Comparison under Hydraulic Disturbance. In August 2013, hydraulic disturbance tests were carried out in No.1 diversion system in Xianyou; In the same boundary, field test values and numerical calculation results under hydraulic disturbance condition are shown in table 2 and figures 9–10.

| Condition | Test value (MW) | Numerical result (MW) | Error value (MW) |
|-----------|----------------|-----------------------|-----------------|
| C1        | 288.13         | 304.23                | 15.60           |
| C2        | 363.30         | 389.82                | 26.52           |

![Figure 9. Opening of disturbed unit (C2).](image3)

![Figure 10. Output of disturbed unit (C2).](image4)

It can be seen that the wicket gate opening changing as time to keep the output constant. The nu-
Numerical result is close to and slightly larger than that of the test, for there is a certain delay of the wicket gates opening in the adjustment. As time changes, the numerical results are in good agreement with that of the test. The numerical calculation results can be used to predict extreme hydraulic disturbance conditions.

4. Conclusions
In this paper, several key simulation technologies of the hydraulic transients were introduced in detail. Based on 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 accelerate 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) The inversion results are in good agreement with the field test values, verifying the reliability of the transition process simulation software HYSIM. The numerical calculation results can be used to predict extreme conditions.

The study provides experience in numerical simulation and analysis of hydraulic transients in other water conveyance systems.

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