Spherical Valve Stability during Hydrodynamic Closure Process

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Abstract. Normally in pump-storage power plant, spherical valve is installed in the terminal of penstock. Spherical valve is used to block the water flow or involving in regulation guarantee. The stability of spherical valve is of great importance for safe operation of pump-storage power plant and unit. In this literature, two kinds of implementation for spherical valve hydrodynamic closure method were discussed, and comparisons of methods were made. On the emphasis of safety, method of shut-down unit was employed for the case pump-storage power unit. For data achieved in hydrodynamic closure with rated load, characteristic analysis of time domain and spectrum analysis of frequency domain were used. The research indicates that on the guide vane failure with load the spherical valve can effectively block water passing passage and the spherical valve displacement meets the requirement of safe running. The maximum pressure pulsation and vibration happens at the spherical valve opening of 34%. Many frequencies occurred in the pressure and vibration signals, including frequencies of rotational stall and rotor stator interference frequency. Considering on the severe vibration of spherical valve, it is recommended that the spherical valve should not involve in the regulation guarantee so as to keep the power plant safety.

1. Introduction
Spherical valve is one of the most important equipments in the pumped-storage power plant. It is vital to the safe running of the unit and power plant [1]. In Chinese standard, it states that under any circumstance the spherical valve should hold the ability to block water passing during hydrodynamic closure process [2]. Therefore, for pumped-storage power plant a spherical valve should be selected to perform the hydrodynamic closure test after the commissioning of the whole units and before the commercial running. Spherical valve hydrodynamic closure test is the test item of great risks, which is classified into the fourth level security event in State Grid Corporation of China.

By now, main researches of spherical valve are focused on two aspects. One is the spherical valve involving in regulation guarantee of transient working points without considering stability of spherical valve. These discussions can be found in articles from Zhang Chun [3], Han lingli [4] etc. The other is inner fluid structure calculation and its verification for different spherical valve opening, for example, Feng Weimin has optimised closing principle of spherical valve and provided numerical simulation results [5], Ming-Jyh Chern has investigated the fluid status inside the spherical valve [6]. Recently,
several literatures have been released about the on-situ observations of spherical valve hydrodynamic closure which happened at Zhanghewan [7], Heimifeng [8], Guangzhou [9], etc. These articles introduced the implementation methods and some gross test results. In our paper, we systemically summarised the test methods based on former reports, and put forward the recommended method to carry out the spherical valve hydrodynamic closure test. Meanwhile, we discussed some influence factors that affect spherical valve stability.

2. Methods on spherical valve hydrodynamic closure test
In China, except Baoquan pumped storage power station, all the spherical valves in pumped-storage power plants were designed without involving in unit regulation guarantee. The failures to the action of spherical valve hydrodynamic closure arise from two sources. One is unit running with speed governor system failing to respond scheduled guide vane opening, after that the unit monitoring system classifies the failure to be guide vane failure, and sequence of spherical valve hydrodynamic closure is triggered to stop unit with reliability. The other one is that the control system of spherical valve fails in normal running by turbine mode or pump mode which causes the servomotor action of spherical valve to block water. For the first scenario, once electrical failure occurring, considering about that all the guide vanes are not under control, the spherical valve should able to block water under the unit full load running. For the second scenario, the emergency stop sequences of monitoring system will be triggered to close guide vanes to specified value or decrease load to specified value, and then generator circuit breaker will be opened. Comparing the two scenarios, the first one is much more dangerous. In view of that test of spherical valve hydrodynamic closure is to check the unit reliability in extreme condition with spherical valve as the last effective equipment to stop the unit, the test should be performed under extreme condition with sequences confirmed and execution device checked. Once the load rejection happening with the guide vane failing to respond, the unit will be in great risk and may result in irreversible destroys. Therefore, a feasible method for carrying out the spherical valve hydrodynamic closure test is showed as follows:

1. Dismantle protections related to spherical valve hydrodynamic closure in generating mode, and set both the spherical valve and speed governor at manual operation mode.
2. Start the unit and keep the unit running under specified load (rated speed idle running excited, 50% rated load running, 100% rated load running) for 15~30 minutes.
3. Manually operate the spherical valve to make the unit load to be zero or to specified small value, and then trigger the emergency stop sequences.

The spherical valve functions and monitoring sequences can be effectively checked by above steps with minimum damages and controlled risks for the unit. In step 3, some engineers choose to transfer unit to SCP (Synchronous Condenser Pump) mode running [10], which can also confirm the spherical valve functions of hydrodynamic closure. Normally, the spherical valve does not design as a tool to regulate flow rate. Once the spherical valve dynamic closing occurred, the guide vane is not controllable, and unit is in huge risk. So, the reasonable method is to shut down unit to make the unit under controllable condition. Meanwhile, after closing the spherical valve, power absorption will increase obviously, and pressure pulsations will be created in passage which may result in destroy of water passage components. In this paper, we described a test performed by above mentioned steps and analysed the recorded data.

3. Test conditions

3.1. Parameters of spherical valve
The test was implemented on a spherical valve of two double-action servomotors with constant closure pressure. The nominal diameter is 2.6m. The rated operation oil pressure is 6.3MPa. The designing water head is 784m and withstand test pressure is 1176m. Total assembly weight is 165t. The open time is 64s and closure time is 53s. The maintenance seal and working seal are driven by water
pressure. Seal action pressure should be larger than 5.2MPa. The servomotor stroke of lever arm is 2293mm.

3.2. Parameters of pumped-storage unit
In turbine running mode, the rated output is 382.7MW, the rated water head is 428m, the flow rate is 96.34m³/s, and the rated speed is 375RPM. The runner blade number is 9 and the guide vane number is 20.

3.3. Test schematic
In order to monitor stability parameter trend during spherical valve hydrodynamic closure, pressures located downstream and upstream of spherical valve, displacement of spherical valve foundation and vibrations of spherical valve have been measured simultaneously with sampling frequency 5000Hz. Refer figure 1 for sensor distributions.

In figure 1, abbreviated symbols represent the following measurement points:
- \( P_1 \): Pressure sensor located at upstream of spherical valve
- \( P_2 \): Pressure sensor located at downstream of spherical valve
- \( V_1 \): Vertical vibration sensor located at the top of spherical valve
- \( H_1 \): Horizontal vibration sensor installed parallel to the flow direction
- \( H_2 \): Horizontal vibration sensor installed perpendicular to the flow direction
- \( S_1 \): Displacement sensor used to measure the foundation movement

For the vibration, we used acceleration sensor PCB 353B33 with frequency response 1~4000Hz(-3.0dB). For the water pressure, we used pressure transducer PTX5072 with frequency response 0~5kHz(-3.0dB) and accuracy of \( \pm 0.2\% \). For the spherical valve foundation displacement, we used displacement transducer LVDT with accuracy of \( \pm 0.25\% \). For the servomotor stroke of spherical valve, we employed rope-operated displacement transducer with accuracy of \( \pm 0.25\% \). The data was collected by NI9208 manufactured by National Instrument. The data acquisition device has a A/D resolution of 16 bits.

The test was performed with upstream water level 658.8m and downstream water level 202.6m.

4. Data Analysis
The spherical valve hydrodynamic closure tests were performed three times with initial unit conditions varying as rated speed idle running excited, 50% and 100% rated load. The initial condition of idle running excited is used to confirm the reliability of test program and robustness of data collecting system. The initial conditions of 50% and 100% rated load are used to confirm the spherical valve capability of blocking water at low and high flow velocity separately. In this segment, we pay much
attention at test with initial condition of 100% rated load, because huge vibrations and pressures occur in this test run.

The condition parameter trends of unit and spherical valve during test are shown in figure 2.

![Figure 2. Trends of condition parameters](image)

From figure 2, we get the following information:

- The servomotor acts linearly by time. For the generator circuit breaker is on, the rotational speed keeps constant and active power decreases with the spherical valve opening reducing.

- During the test, without considering on the turbine efficiency variation, the active power is proportional to the multiplication of flow rate and working head. From the figure, we see that there is intersection between active power and spherical valve opening, mainly the cross point near spherical valve opening of 50%. The cross point means that the load regulation capability of spherical valve in opening above 50% is weaker than that in the opening below 50%.

- On active power to be 4% rated power, mechanical failure sequence has been triggered and guide vane operated to close.

In the whole process of spherical valve hydrodynamic closure, refer figure 3 for pressures of passage, vibrations of spherical valve and displacement of spherical valve. The peak-to-peak values with 95% confidence level are being indicated in figure 4.

![Figure 3. Trends of pressure measurements, spherical valve displacement and vibrations](image)

![Figure 4. Trends of peak-to-peak values of pressures, vibrations and spherical valve opening](image)
foundation. On the spherical valve fully close, the spherical valve bears maximum axial hydraulic thrust and the foundation displacement of spherical valve reaches maximum value 1.57mm. The displacement complies with safe operation as less than 3.5mm. In the former 30s, with the spherical valve closing, upstream pressure of spherical valve has a trend of increasing, while downstream pressure of spherical valve has a trend of decreasing. This phenomenon means that in the former 30s, with the spherical valve closing, unstable turbulent flow occurs in the upstream of spherical valve, which results in water hysteresis with higher pressure, pressure pulsation and hydraulic loss improvement [11]. Meanwhile, vortex occurs in the downstream of spherical valve, and the vortex dimensions have direct relation with spherical valve opening. In the larger opening zone, with spherical valve opening decreasing the vortex becomes larger and brings huge pressure pulsation in passage and vibration in spherical valve body. In smaller opening zone, the vortex vanishes with the spherical valve opening decreasing and flow becomes to be jet flow, which results in decaying pressure pulsation and vibration of spherical valve. Figure 4 shows peak-to-peak values of pressures and vibrations. It can be obtained that on the opening to be 34% the pressure pulsations and vibrations reach extremes and the turbulent flow intensity reach maximum.

In order to investigate the frequency component change during period of spherical valve hydrodynamic closure, short-time-Fourier-transform has been employed for the time-variant signals considering that the whole process is typical unstable. The window function used is Hanning function. The window width is 1s and the step is 0.1s. Refer figure 5 for details.

From figure 5, following results can be drawn:

- The frequency components of P1 and P2 concentrate on low frequency span (less than 50Hz). For P1, the main frequencies are 30Hz and 4.4Hz; for P2, the main frequencies are 12.5Hz and 4.4Hz. Rotor-stator interference frequency (RSI frequency is two times runner blade passing frequency) is vague in both points. The 30Hz component in P1 is mainly related to natural frequency of spherical valve and water. The 4.4Hz component is 0.7 times rotational frequency, which may come from rotational stall happening in the vaneless zone. Frequency components in P2 is more complex than that in P1, which indicates that flow condition at downstream is more turbulent than that at upstream of the spherical valve.
- Peak-to-peak values of V1 and H2 have the same trend as shown in figure 4(b), and frequency components also have the same contents. Therefore, in the paper researchers put spectrum of V1 for reference. During the hydrodynamic closure period, frequency contents become more complicated, especially at the maximum vibration moment. Typical induced frequencies include RSI frequency.
112.5Hz, 176.6Hz (This is the natural frequency of power house.) and some frequencies ranging from 60–90Hz.

5. Conclusions
In this paper, we detailed analysed implementation methods of spherical valve hydrodynamic closure test in view of safety of unit, spherical valve and power house. Feasible test sequences were proposed. The test was performed by the proposed method at Xianju pump-storage power station. Characteristic value analysis technique and short-time-Frequency-transform were employed for signals about spherical valve vibrations, pressures. The results show that on guide vane failure the spherical valve can block water with reliability and the displacement of spherical valve meets the requirements of safe operation of unit; the pressure pulsation reaches maximum on the spherical valve opening to 34%; many frequencies occur in the signals, including characteristic frequencies of rotating stall, rotor stator interaction frequency, etc. Considering that the spherical valve vibrates more severe in process of hydrodynamic closure than in normal running, it is recommended that during the commercial running of the unit spherical valve is not suitable for guarantee regulation in transient working points and load regulation in stable working points, so as to avoid irreversible defects.

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