Effects of Pump-turbine S-shaped Characteristics on Transient Behaviours: Model Setup

Wei Zeng, Jiandong Yang, Jinhong Hu
State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, China
wzeng@whu.edu.cn

Abstract. Pumped storage stations undergo numerous transition processes, which make the pump turbines go through the unstable S-shaped region. The hydraulic transient in S-shaped region has normally been investigated through numerical simulations, while field experiments generally involve high risks and are difficult to perform. In this research, a pumped storage model composed of a piping system, two model units, two electrical control systems, a measurement system and a collection system was set up to study the transition processes. The model platform can be applied to simulate almost any hydraulic transition process that occurs in real power stations, such as load rejection, startup, frequency control and grid connection.

1. Introduction

To adjust the power system more efficiently and in a timely manner, pumped storage stations undergo numerous transition processes. Many engineering incidents occur in the process, such as turbine lifting accidents as a result of hydraulic transients and unsuccessful grid connections under low head. Therefore, it is important to investigate these transition processes to guarantee the security of the pumped storage station.

The S-shaped characteristics of the pump turbine are a critical factor in determining the transient characteristics of pumped storage stations. Different simulation methods have been applied to study the transition process in the S-shaped region [1-4]. Moreover, field experiments have also been conducted to obtain additional verification. Dörfler et al. partly closed the valve in the field to achieve pump turbine no-load stability [5]. Yang et al. analyzed the pressure pulsation characteristics of a prototype pump turbine during a transition process [6]. The transient experiments of load rejections and power failure must be performed in the commissioning stage to ensure safety and stability [7]. However, owing to the risks involved in field experiments, it is difficult to conduct experiments for specific engineering problems and some extreme conditions.

To compensate for the limitations of field experiments, the corresponding model experiments can be developed. The existing model experiment platforms for hydraulic machineries are generally closed-loop test rigs, which are mainly used to test the turbine characteristics in the constant states [8,9]. To study the transition processes of a Francis turbine, NTNU changed the piping system on the basis of the closed-loop test rig to set up the open-loop test rig. The model is used not only to test the turbine characteristics but also to measure the pressure pulsations at constant states [10,11] or during startup and load rejections [12,13]. However, some complex transition processes in actual pumped storage stations are difficult to achieve.
In summary, to investigate the transient characteristics of pump turbines and pumped storage stations, a more realistic pumped storage system is developed and introduced in this paper.

2. Basic information

The pumped storage system illustrated in Fig. 1 consists of model pipes with circulating water, model units (pump turbines and motor generators), a control system (excitation synchronization protection, frequency and phase conversion, speed control, monitoring system, load system), and a measurement system. The major functions and components of each system are shown in Table 1.

| No. | Subsystem                      | Main functions                                                                 |
|-----|--------------------------------|--------------------------------------------------------------------------------|
| 1   | Model pipe                     | Simulates the actual power station pipes and supplies water to the model pump turbines |
| 2   | Circulating water system       | Supplies power and water circulation for model experiments                      |
| 3   | Model units                    | Includes two sets of pump turbines and motor generators                          |
| 4   | Excitation and synchronization  | Excitation control, synchronization, and protection of the motor generator       |
| 5   | Frequency and phase conversion | Varies frequency startup in pump mode and conditions transformation in turbine mode |
| 6   | Speed control                  | Controls the speed governor to regulate the guide vane opening and regulates the ball-valve opening degree |
| 7   | Local control unit (LCU)       | Gives orders to the model units and controls them                                |
| 8   | Load system                    | Simulates the grid features                                                     |
| 9   | Measurement system             | Collects and processes the parameters                                           |

3. Experimental platform setup

3.1 Model pipes with circulating water

The pipe system of the pumped storage system model employs an annular arrangement pattern of two machines sharing the same main pipes. The section area of the downstream impedance surge tank is 0.43 m², and the impedance hole can be turned on or off through a valve according to the experimental requirements; the hole is normally closed. The model pipe system is mainly designed based on the pipe layout of the Xianju pumped storage station with the distorted scale including the radial scale.
1:17.357 and the axial scale 1:42.366. The pipe system is shown in Fig. 2, and the main dimensions are shown in Table 2.

![Pipe system diagram](image)

**Figure 2.** Model 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 |

The circulating water system primarily provides water circulation for model experiments. Water is pumped from the underground reservoir by centrifugal pumps and supplied to the upstream and downstream tanks through the supply pipe (Fig. 1). The valves on the supply pipe can adjust the flow into the upstream and downstream tanks. Overflow weirs are installed in the tanks to maintain a constant water level, and the overflow out of the weirs flows into the underground reservoir through the draw-off pipes.

### 3.2 Model units

Two model pump turbines installed in the platform were obtained from the Harbin Electrical Corporation, Harbin, China. They are the pump turbine models at the Xianju pumped storage station (XJ) and the Baoquan pumped storage station (BQ). Both pump turbines basically have similar characteristics in the turbine high efficiency area, but differ significantly in the S-shaped region. The runner geometries are also distinct; these details are shown in Fig. 3. The basic parameters of the two pump turbines are presented in Table 3.

![Model runners](image)

**Figure 3.** Model runners

| $N_{ge}$ (m$^3$/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) | Full rotational inertia (N.m) |
|---------------------|---------------------|----------------------|------------------------|------------------|----------------------|-----------------|---------------|-----------------|-----------------------------|
| 37.91               | 280                 | 146.34               | 24.44                  | 9                | 20                   | 1000            | 10.54         | 49.1            | 66.4                        |

### 3.3 Control system

Each unit has a set of electrical cabinets to control the unit operation, including the local control unit, speed control system, excitation system, and load system. Their basic functions have been presented
in Table 1. These systems can make the model units implement almost all the operations and conditions encountered in real power plants. The load system includes resistances, capacitances, and inductances to simulate an isolated grid with different characteristics by varying load combinations. In addition, the units can be also incorporated into the state grid, as shown in Fig. 1.

The PC-III programmable microprocessor speed governor (Fig. 1) is employed to control the pump turbine guide vanes with proportional–integral–derivative control. Its main function is to automatically track the grid frequency after unit startup and to achieve the best process control of startup, fast quasi-synchronization, frequency regulation (isolated network), power regulation, as well as opening degree regulation. In the experiments, the opening degree regulation function can dominate the guide vanes by various means, such as stalling, straight closure, and multi-phase closure.

4. Measurement of experiment data

4.1 Pressure measurement

The PCB 112A pressure sensors and MPM 480 pressure sensors were used to test the transient pressures, and the KYB 335 sensors were used to test the differential pressure of two points at the same section of the spiral case. The Fluke 719 pressure calibrator was used to calibrate the pressure sensors in the field. In the pipe systems, the main pipe, branch pipe, surge chamber, and upstream and downstream tanks were equipped with a certain number of MPM pressure sensors. MPM pressure sensors and PCB pressure sensors were installed on the points shown as Fig. 4 and Table 4. Table 5 presents the basic specifications of the major sensors used in the present tests.

| No. | Sensor type | Position                      |
|-----|-------------|-------------------------------|
| 1   | MPM 480     | Spiral case inlet            |
| 2   | PCB 112A    | The bottom of the spiral case |
| 3   | KYB 335     | Two points at the same section of the spiral case |
| 4   | PCB 112A    | stay vane                    |
| 5   | PCB 112A    | Vaneless space 1             |
| 6   | PCB 112A    | Vaneless space 2             |
| 7   | MPM 480     | Draft tube inlet 1           |
| 8   | MPM 480     | Draft tube inlet 2           |
| 9   | MPM 480     | elbow bend 1                 |
| 10  | MPM 480     | elbow bend 2                 |

Figure 4. Pressure sensor positions

Table 4. Pressure sensor types and positions
### Table 5. Specifications of the different sensors

| Sensor type                      | Positions                        | Measurement range  | Accuracy  | Linearity (%) | Uncertainty (%) | Signal          |
|----------------------------------|----------------------------------|--------------------|-----------|---------------|-----------------|-----------------|
| Pressure sensor (Micro MPM 480)  | 1# Spiral case inlet             | 0–200 (kPa)        | 0.25      | 0.052 F.S     | 0.109           | 4–20 mA        |
|                                  | 1# Draft tube inlet              | −20–50 (kPa)       |           | 0.035 F.S     | 0.083           |                |
|                                  | 2# Spiral case inlet             | 0–200 (kPa)        |           | 0.051 F.S     | 0.079           |                |
|                                  | 2# Draft tube inlet              | −20–50 (kPa)       |           | 0.053 F.S     | 0.621           |                |
| Flow meter (KROHNE IFM 4110)     | Upstream main pipe               | −200–200 (L/s)     | 0.3       | 0.128 F.S     | /               | 4–20 mA        |
| Flow meter (OPTIFLUX 2000)       | 1# branch pipe                   | −70–70 (L/s)       | 0.2       | 0.157 F.S     | /               | Frequency       |
|                                  | 2# branch pipe                   | −70–70 (L/s)       |           | 0.141 F.S     |                 |                |
| Torque sensor (HLD09)            | Between 1# turbine and 1# generator | −100–100 (N.m)   | 0.2       | 0.040% F.S    | /               | 4–20 mA        |
|                                  | Between 2# turbine and 2# generator | −100–100 (N.m)   |           | 0.020% F.S    | /               | Frequency       |

4.2 Flow measurement

Two electromagnetic flowmeters (Table 5) were installed in the model power station to measure the flows. To improve the accuracy of the experiment and to calibrate the electromagnetic flowmeters, a flow measurement device (Fig. 5) was developed by the static weighing method. To measure the forward flow (turbine direction), the supply valve of the downstream tank was closed and the flow passing through the units was drained from the draw-off pipe in the downstream tank. The draw-off pipe connects inlet A of the device and the drained water from outlet B are weighed. The opening and closure times of outlet B are $t_1$ and $t_2$, the entire opening duration is $t_0$, and the weighed water is $m$. Thus, one can get

$$Q = \frac{m}{\rho(t_0 + t_1/2 + t_2/2)} \quad (1)$$

Here, in the flow calibration test, $t_0 > 60$ s, $t_1$ and $t_2$ are less than 0.1 s, and the accuracy of the electronic scale is smaller than 0.05%. The calibration results for the electromagnetic flowmeters using such an apparatus are listed in Table 5.

A more precise measurement of dynamic flow is obtained by minimizing the time constant of the electromagnetic flowmeters to achieve the fastest response. However, there are always some delays in electromagnetic flowmeters. Therefore, the differential pressure sensor was installed in the spiral case to measure the dynamic flow. However, its accuracy is much lesser than that of the electromagnetic flowmeters. Nevertheless, the flow peaks and valleys measured by the differential pressure sensors can be used to calculate the delay time of the electromagnetic flowmeters. Thus, the delay response can be eliminated by adjusting the time coordinate.

![Flow calibrator](image)

4.3 Speed and torque measurements

The HLD09 speed-torque sensor was installed between the turbine and generator, in which the torque applies the strain electrical logging principle: a strain gauge installed in a special shaft deforms with the torque and the resistance changes accordingly. The speed-torque sensors were calibrated as factory default, as shown in Table 5.
4.4 Guide vane movement measurement

The guide vane angles during transients were tested by the angle transducers installed on the top of the guide vane shaft. Using the standard gauge blocks, we obtained the relationship between the guide vane opening and the guide vane angles.

5. Data acquisition and processing

5.1 Data acquisition.

Different analog signals from these sensors were collected by a HBM Gen7i data acquisition system with a 24 bit analog-to-digital resolution, a 250 kHz maximum sampling frequency, and 70 channels. As the experiments in this study focused on the water-hammer pressure, rotational speed, and torque with low frequencies, we chose a 1 kHz sampling frequency because it is adequate for the experiments in this study.

5.2 Data processing.

Based on the previous studies by Trivedi [10-13], the Savitzky-Golay method [14] was used to extract the pressure pulsation in the transition process. The Savitzky-Golay method is a low-pass filter method that performs polynomial fitting of the original data, extracts the timed mean pressure based on the least squares method, and then obtains the pulsating pressure according to the differences between the original data and the timed mean pressure. Fig. 6 shows the measured value of the spiral case pressure and the filtered results by the Savitzky-Golay method under the condition that the one pump turbine with partial rotational inertia rejected the load with the guide vanes closed in 3 s.

![Figure 6. Savitzky-Golay filtering](image)

6. Conclusions

In the present study, a pumped storage model was built to study transition processes of a pumped storage station. The model composed of two pump-turbine scales, two motor generator scales, pipe system and control system is available to conduct a variety of transient experiments happened in the real pumped storage stations. The transient pressures, flow, torque, rotational speed and guide vane movement can be tested with high precisions.

In the next paper, the author would introduce the transient experiments conducted on the model to investigate the effects of pump-turbine S-shaped characteristics on hydraulic transients.

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