Transient approach for identification of the S-shape region of pump turbines

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Abstract. A new approach for identification of the S-shape region of pump turbines by means of transient tests is presented. The behavior of pump turbines is characterized by the S-shape region that is passed during load rejection. The mechanisms within the S-shape region are still part of basic research. Beside the known Thoma number dependency, further non-linear effects in terms of a hysteresis loop in the S-shape region are suspected. Since the S-shape region is passed in both directions during load rejection a hysteresis behavior would influence the water way dynamics. The common approach by measuring various steady points is not able to capture this non-linear effect. Therefore, a transient approach for model tests is investigated. Within this paper the transient model test procedure is described and the results of the model test are shown. Since the transient behavior is superimposed by high frequent pressure fluctuations, special focus is on the evaluation of the measurement data. Finally, the influence of the hysteresis behavior on the simulation results of water way dynamic system is shown.

1. Introduction
For safe operation of hydro power plants the reliable prediction of speed rise and of pressure rise in the spiral case and penstock due to water hammer in case of load rejection or emergency shut down is essential. This prediction is a challenging task especially for pump turbines since typically a S-shape region is passed [1, 2]. In this case, the pressure rise due to reduction of the discharge is not only controlled by the closing of distributor but also depending on the shape of the hill chart in this region [3].

As shown previously in [4] the utilization of the measured unit characteristic for the calculation of maximum pressure and speed rise result only in small deviations compared to the recorded signals during commissioning at the prototype. The accuracy of the prediction can be improved by an adjustment of the S-shape region of the hill chart. This modification is motivated by capturing the influence of the Thoma number on the S-shape characteristic. A detailed analysis of the Thoma number influence has been carried out in [5].

However, there are some pump turbines where this positive effect of the Thoma number adjustment has not been observed [4]. Therefore, other influences on the transient behavior have to be investigated.

The S-shape region is passed in a transient event during load rejection several times in both directions (from turbine mode to reverse pump mode and vice versa). Since the hill chart is usually set up by a number of measured steady state points, transient effects in terms of a possible offset or even a hysteresis loop are not included in the hill chart. To get a better understanding of the dependencies of the S-shape characteristic, the influence of transient phenomena on the
characteristics in the S-shape region of pump turbines are addressed in this paper. At first, a transient test at the test rig in the lab is designed and performed. Next, results of the tests as well as the procedure for their evaluation are shown and the observed changes in the characteristic are discussed. Finally, a comparison by means of numerical simulation is performed to qualitatively investigate the influence of the transient recorded hill chart on the speed and pressure rise during load rejection.

2. Transient model test
The test procedure to capture the dynamic behavior of a pump turbine passing the S-shape region in different directions is shown in this section. The tests were carried out at a universal test rig at Voith Hydro in Heidenheim. A pump turbine model with 9 blades and 20 gates was utilized. In the following section the test procedure, test results and their evaluation are shown.

2.1. Model test description
The conducted tests focus on the transient behavior of a pump turbine in the S-shape region. It is intended to pass through the S-Shape region in a transient event on the test rig. Starting from an operating point in turbine mode there are two options to pass the S-shape region, if the gate position is intended to be kept constant. On one hand, similar to the situation at load rejection at the prototype, the rotational speed can be increased. On the other hand the head at the turbine runner can be reduced while rotational speed is kept constant. For the present analysis the second option is chosen for the investigation since the head can easier be controlled by adjusting the service pump. Furthermore, the reduction of the head during the tests gives additional safety regarding the structural health of the test rig since the pressure level drops during the test.

In figure 1 the test rig configuration for the test is shown.

![Test rig configuration for S-Shape tests.](image)

The pump turbine model is placed between two water tanks. In the tailwater tank atmospheric pressure was present during the tests. Since the flow meter is located in front of the headwater tank, the headwater tank was entirely filled with water such that the inflow water is directly transferred. Furthermore, the test rig is equipped with a service pump that is used to adjust the discharge at the pump turbine. The test rig also contains a parallel pipe with
a throttle valve. It is essential for this test in order to conduct the water to the tailwater side with the pump turbine in reverse pumping mode.

During the test the discharge is measured by the magnetic induction flow meter. For the measurement of the head at the pump turbine the common setting is used. Furthermore, two sensors for total pressure were installed at inlet pipe and at the flow meter as back up for the transient discharge measurement. Additionally, rotational speed, torsional moment and wicket gate position were measured.

For the tests the required discharges at the service pump for one operating point in turbine mode and one in reversed pump mode at the wicket gate opening under investigation were determined. Then, the discharge of the service pump is alternated between these two points and the system behavior is recorded. Overall, three repetitions were carried out for each wicket gate opening. This test procedure is then repeated for several wicket gate openings.

2.2. Evaluation procedure of test results

In figure 2 the discharge $Q$ and the pressure difference $\Delta p$ at the pump turbine during a test is shown. In this case the S-shape region is passed from turbine to reversed pump mode. The measured discharge shows an almost smooth behavior. In contrast, the measured pressure is significantly influenced by high frequent dynamic pressure oscillations. The pressure fluctuations are only an indicator for the high frequent oscillations but they are not resolved adequately by the applied pressure sensors since the pressure sensors are designed for static head measurement with low frequency resolution. Since a transient test is performed the measured pressure difference is influenced by acceleration and deceleration of the water masses in the runner. Therefore, the measured pressure difference is adjusted by mass inertia of the water in the runner and time derivative of measured discharge. Furthermore, the geodetic head between the different heads of the fluid levels on pressure and suction side of the pressure measurement has to be considered for the pressure difference.

In figure 3 unit flow $q'_1$ and unit speed $n'_1$ are plotted in a hill chart. The unit flow is defined as

$$q'_1 = \frac{Q}{D^2\sqrt{\Delta p_0/\rho/g}}$$

and the unit speed is given by

$$n'_1 = \frac{n D}{\sqrt{\Delta p_0/\rho/g}}.$$
Herein, \( D \) denotes the inlet diameter of the runner and \( n \) is the speed during the test. The constant of gravity is defined as \( g \) and \( \rho \) denotes the density of water. Further, the modified pressure difference \( \Delta p_0 \) due to water inertia and geodetic head is used.

Obviously, the fluctuations in the measured pressure strongly affect the characteristic. Therefore, some further efforts had to be made for the evaluation.

\[
\Delta p_0 = g \Delta h + \rho \frac{q}{2} \frac{d}{n^2},
\]

In order to obtain a characteristic line for each analyzed wicket gate opening a polynomial approximation is applied. In detail, \( n'_1 \) is approximated depending on \( q'_1 \) via

\[
n'_1(q'_1) = \sum_{i=0}^{d} c_i (q'_1)^i.
\]

Due to the general behavior of the S-shape odd values of the maximum degree \( d \) of the polynomial are reasonable. The constants \( c_i \) are obtained by a best fit of the curve to the measured data by least square method. In figure 3 the approximation of the raw data by increasing degrees of the polynomial is shown. A polynomial degree of at least \( d = 7 \) is required. In the following, the evaluation is performed for a polynomial degree of \( d = 9 \).

The same approach is also used for processing the measured torque.

2.3. Test results

In figure 4 the results of the evaluation for two wicket gate openings are illustrated. Within each diagram one transition from turbine to reversed pump mode and back is shown. Since all repetitions of each test ended up in almost the same result, the results of the repetitions are skipped in the diagram. The corresponding behavior as it is observed by steady measurement of several points in the S-shape region is also plotted. It is denoted by “steady measurement”.

For the higher wicket gate opening a good agreement between both transitions is observed and only in the region below zero discharge a small hysteresis is noticed. Here, the transition from turbine to reversed pump mode shows slightly higher \( n'_1 \) values. For the smaller wicket gate opening the transition from turbine to reversed pump mode shows higher \( n'_1 \) values for a wider region.

In both cases, a very good agreement is observed between the transition from reversed pump mode to turbine mode and the steady measurement. The good agreement confirms the reliability of the transient test procedure.

Based on the identified S-shape characteristic two hill charts are created. The first one considers the transition from turbine to reversed pump mode. The second one includes the characteristic of the reversed direction. These hill charts are then used in the following section to check the influence of the hysteresis on the dynamic behavior of a pump turbine during emergency shut down.
3. Influence of hysteresis on power unit behavior

In order to investigate the influence of the hysteresis loop on plant relevant design parameters the identified hill charts are used for simulation of a emergency shut down. A pump storage plant with 4 units connected to a common headrace tunnel is considered. For this analysis one unit is operating at rated output while the remaining 3 units are at stand still condition when a sudden load rejection occurs.

In figure 5 the speed during such a transient event is plotted. Figure 6 shows the pressure in the spiral case. Both figures compare the results based on different hill charts.

The results for the S-shape characteristic that is present if the S-shape is passed from reversed pump to turbine mode are denoted by HC uw. If the hill chart in which the S-shape is measured from turbine towards reversed pump mode is used in the simulation then the results are indicated by HC dw. The results also including the hysteresis loop in the S-shape region are named as HC hl.

A slightly higher maximum value is obtained for the speed rise if the upward characteristic in the hill chart (HC uw) is applied for the entire transient event.

Speed oscillations continue to be higher compared to the other simulations. The utilization of the hill chart that considers the hysteresis loop leads at first to the identical speed rise compared to the downward recorded hill chart since the identical shape of the hill chart is used. Afterwards lower oscillations are observed due to the hysteresis.

A similar behavior is observed for the transient behavior of the pressure in the spiral case (cf. figure 6). The peaks are highest if the S-shape characteristic with the transition from reversed pump to turbine mode is applied. Only small differences are noticeable between the
results if the downward or the full hysteresis characteristic is applied.

Overall, conservative results regarding maximum overspeed and pressure rise in the spiral case are obtained by utilization of a hill chart measured from reversed pump to turbine mode.

4. Summary
A transient procedure to identify the S-shape characteristics at a test rig has successfully been developed. Within this approach the S-shape region is passed in both directions while wicket gate openings are kept constant. A hysteresis loop has been detected in the vicinity of zero discharge. Nevertheless a good agreement of the identified characteristics for the transition from reversed pump mode to turbine mode with steady state measurements has been observed.

By applying a hill chart including the hysteresis for simulation of an emergency shut down at a pumped storage power plant, oscillating pressures in the system and speed rise have been determined. Differences are negligible if results are compared to the simulation with a hill chart in which points are measured from turbine to reversed pump mode. Major differences are observed if the results are compared to the simulation with a hill chart that is determined from reversed pump to turbine mode.

Based on this basic work further investigation will be carried out to compare the simulation
approach with such detailed hill charts with prototype measurements. Additionally, a combined simulation approach considering the known Thoma number dependency is intended for more accuracy in the prediction of the transient behavior.

References
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