Water flows generating hysteresis on the S-shape

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Abstract. For a given hydraulic design and a given guide vane opening, pump-turbine S-shape description in the turbine quadrant can be different depending on whether measurements are performed from the high discharge to the low discharge area or vice versa. A specific device for visualizing the flow field inside the runner has been developed in a scaled model of a medium head pump turbine machine in order to analyze and understand this hysteresis phenomenon. Windows, lights, high-resolution cameras and tracers have been combined to visualize the flow field. Flow field behavior has been studied in the runner and in the vaneless area located between the guide vanes and the runner. Two different methods of analyzing the flow field in the runner have been tested. Depending on the localization of the operating points and the direction of the S-shape description, different flow structures have been directly observed. In parallel, a study of the impact of this hysteresis on transient behavior in turbine mode has been carried out. Understanding this phenomenon is important to improve future design and to accurately measure the S-shape during model tests.

1. Introduction

In order to properly operate a pump-turbine, it is essential to know its four quadrants’ characteristics. Depending on the water head, the discharge through the runner and its rotational speed, the operating points of a pump-turbine and its hydraulic efficiency can vary a lot. Thus, model tests on a hydraulic test rig, according to IEC 60193, allow a complete mapping of pump-turbine characteristics. Results of the tests performed on a medium head pump-turbine, designed by SuperGrid Institute, and tested on the SuperGrid-CREMHyG test rig (Grenoble – France) are shown here below (Figure 1).

![Figure 1. S-shape curves and hysteresis in the turbine quadrant of a medium head pump-turbine](image_url)
In the turbine mode quadrant, it was observed that characteristic curves may be different in the region of the \( n_{\text{ED-Max}} \), depending on how the tests are performed. For a given guide vane opening, S-shape characteristics can be different depending on whether measurements are performed from the high discharge to the low discharge area or vice versa (Figure 1, right). It is important to analyze and to understand this hysteresis phenomenon but it is also important to investigate its impact on transient behavior during load rejection in the turbine.

In this paper, the hysteresis phenomenon impacting the S-shape characteristic for a large guide vane opening is investigated. First, a summary on the S-shape characteristic is carried out. Then, water flows structures in the runner and in the vaneless gap located between the guide vanes and the runner are experimentally studied and analyzed. Then the impact of such hysteresis on the turbine transient behavior is investigated thanks the analysis of transient simulation results.

2. S-shape

In the turbine and reverse pump quadrants, characteristic curves for a constant guide vane opening have a shape on “S”. Along a characteristic curve from the highest discharge to the lowest discharge, the discharge factor \( Q_{\text{ED}} \) decreases whereas the speed factor \( n_{\text{ED}} \) increases until to reach a maximum value \( n_{\text{ED-Max}} \). From \( n_{\text{ED-Max}} \), \( Q_{\text{ED}} \) and \( n_{\text{ED}} \) decrease until runaway and continue to decrease up to null discharge (\( Q_{\text{ED}} = 0 \)). In the reverse pump quadrant, the characteristics reach a new inflection point before an increase of \( Q_{\text{ED}} \) and \( n_{\text{ED}} \). The shape of this characteristic curve is commonly called the S-shape. Medium to high heads pump-turbines machines (\( N_q \leq 50 \)) usually have pronounced S-shapes.

One condition that is necessary for the stability of an operating point is to have a negative \( dQ_{\text{ED}}/dn_{\text{ED}} \) slope. This is not the case in the region beyond the \( n_{\text{ED-Max}} \) when decreasing the discharge. This area is an unstable operating zone.

Depending on the guide vane opening, drawbacks generated by the S-shape (i.e. a positive \( dQ_{\text{ED}}/dn_{\text{ED}} \) slope) are different.

1. **Turbine start up and coupling to the network (small guide vane openings used):** During the start-up process, the machine is first accelerated until it reaches the synchronism speed imposed by the electrical network. As the turbine is not yet connected to the electrical grid, it is not slowed down by the generator’s electromagnetic torque and only the inertia balances the hydraulic torque. At the speed stabilization point, the counter torque related to inertia reaches zero and the hydraulic torque is the only one to be applied to the shaft line. If the runaway curve crosses the S-shape area with a positive \( dQ_{\text{ED}}/dn_{\text{ED}} \) slope at the coupling, the hydraulic torque of the pump-turbine is unstable. Very strong variations of runner rotational speed can be observed, making it very difficult or impossible to couple the machine to the electrical grid.

2. **Turbine transient behavior (high guide vane openings used):** Case study of a pump-turbine already in operation at full load which is disconnected suddenly from the electrical network. Once the connection has been lost, the electromagnetic torque no longer brakes the runner and the hydraulic torque accelerates the pump-turbine up to the runaway condition. If the runaway curve is on the S-shape (i.e. a positive \( dQ_{\text{ED}}/dn_{\text{ED}} \) slope), the operating point is not stable and so it cannot be maintained. The machine goes through successive states and can switch in the reverse pump quadrant. These changes of state are associated with strong discharge variations that can generate strong overpressure levels in the upstream components (spiral case, penstock) and can generate significant pressure decrease in the downstream component below the runner (draft tube). The unsteady flows that are generated can induce high dynamic loadings which can be responsible for mechanical vibrations and damage the turbine components.

For some decades, the S-shape characteristics of medium and high heads pump turbines have been widely numerically and experimentally studied thanks to scaled model measurements. Among various carried out studies, one can note the studies of Houdeline [1], Li [2], Staubli [3], Guggenberger [4] or
Hasmatuchi [5] for investigations of the S-shape in the coupling area (small guide vane openings). Jacquet [6], Liu [7] and Zeng [8] investigated the S-shape in the area of large guide vane openings.

From these studies, one can note that the S-shape is the consequence of backflows which occur at the runner inlet and in the vaneless area located between the guide vanes and the runner. However, very few studies address a specific feature of the hysteresis phenomenon impacting the S-shape characteristic (Yamabe [9]).

3. Experimental tests

3.1. Test pattern

Tests on a reduced scaled pump-turbine model were performed at the SuperGrid-CREMHyG laboratory (Grenoble). The tested runner was designed by Supergrid Institute with the objective of reducing the S-shape amplitude. The model was equipped with large transparent windows located in the hub, making it possible to visualize the flow field between the runner blades directly (Figure 2). In order to give a better visual access, windows were implemented in the upper head cover. These windows made it possible to visualize the flow field in the vaneless area located between the guide vanes and in the runner channels themselves.

![Figure 2. Test pattern](image)

To visualize the flow field, various markers were tested during the model tests. Fine wires were installed in the runner and micrometric gas bubbles were injected in the vaneless area (Figure 2). The wires used had a 0.1mm diameter and were around 4cm long. Gas bubbles were injected using specifically designed injectors to adjust the injected bubble sizes and quantity in the flow. The size of the micrometric bubbles was defined to be small enough not to disturb flow field, but large enough to be tracked.

The use of wires made it possible to visualize the general flow field quickly. They made it possible to obtain a description of flow structures in the runner, but they were very easily snatched when the discharge level was too large. Other drawbacks for using wires were their local influence on the flow field (only close to the attachment point on the inter-blade channels walls). The advantages and drawbacks of the gas bubbles are opposite to those of the wires. Gas bubbles make it possible to visualize all of the flow field without disturbing it. However, the gas bubbles’ trajectories require a specific post processing before being able to correctly understand the flow structures, especially in the runner.

Below, the results obtained with gas bubbles in the vaneless area and the results with wires in the runner blade channels are presented.

Pictures have been made using high resolution cameras. In order to make the gas bubbles and tufts appear correctly on the pictures, stroboscopic LEDs were used. Finally, in order to assess flow structures, 500 images were overlaid on one same image for each operating point on the S-shape.

3.2. Summary of tests

A large number of S-shapes were performed. In order to correctly describe the turbine quadrant, the S-shape was studied for different guide vane openings.
For a given guide vane opening, measurements were first performed from the high discharge to the low discharge area. The set of recorded operating points describes the S-shape characteristic starting from the discharge value corresponding to the optimum operating point (optimum efficiency point of the given guide vane opening) to the zero discharge level. Measurements included the determination of the maximum $n_{ED-Max}$ point as well as the operating point at runaway.

Then for the same guide vane openings, the S-shape characteristic was measured by increasing discharge. Starting from the zero discharge level, the S-shape characteristic was measured in the reverse direction, until it reached the optimum operating points.

In order to correctly study flows structures in different locations of the model, with different means, overall about 20 S-shapes were carried out in both directions for a same given guide vane opening. All of them are well reproductive. In the $n_{ED-Max}$ area, a hysteresis was observed. This hysteresis was due to different structures of the flow field identified in the runner and in the vaneless gap.

3.3. Flow structures on the hub of the vaneless gap between the runner and the guide vanes

Gas bubbles were injected at the outlet of the guide vanes near the hub (Figure 2 and Figure 3). They follow the flow field from the outlet of the guide vanes to the runner blades inlet without affecting it thanks to their size. Having injected the gas bubbles between the guide vane and the runner, the gas bubbles observed between the circle of the gas injection (“Radius of gas injection” on Figure 3) and the guide vanes (“1 blade side of guide vanes” on Figure 3) are the proof of a water backflow at the hub in this area.

At the optimum operating point (#1 on Figure 3), the cloud of gas bubbles is straight and narrow from the gas injection point to the runner inlet. At this operating point, the flow field does not show any specific disturbance such as flow separation or backflow.

By decreasing the discharge until the start of the S-shape (between #1 and #2 on Figure 3), the flow field changes its trajectory slightly. In addition, the cloud of gas bubbles becomes slightly wider. Therefore, the flow field starts to be slightly disturbed but it remains mainly without flow separation. Despite the constant guide vane opening, the trajectory of the gas bubbles becomes more tangential to the runner inlet and slightly unstable.

Some gas rotating detachments near the runner inlet appear when decreasing the discharge level and entering the S-shape (from #2 to #10 on Figure 3). The size and the number of these gas rotating detachments increase in the S-shape hysteresis area (#3, #4, #5, #9 and #10 on Figure 3). The size and number of gas rotating detachments are similar on both branches of the hysteresis. They decrease from the runaway point (#6 and #8 on Figure 3) to the null discharge point (#7 on Figure 3).

For the operating points outside of the hysteresis zone, the flow field structure is the same depending on whether the S-shape has been measured in increasing or decreasing the discharge. On Figure 3, points #5, #6 and #2 show quasi-similar flow field structures with those of points #9, #8 and #11 respectively. At runaway (# 6 and # 8 on Figure 3) and at zero discharge point (# 7 on Figure 3), scattered gas bubbles can be observed. A large part of the gas bubbles are located between the gas injection circle and the guide vanes. Therefore, a backflow is clearly observed in this area at these operating points. There is a water flow that returns upstream of guide vanes.

Concerning the S-shape hysteresis, gas bubbles in the flow field allow different structures of the flow close to the hub in the vaneless gap to be highlighted. The difference of flow structures depends of the S-shape description. When measurements are performed from the high discharge to the low discharge for S-shape description, (#3 and #4 on Figure 3 as well as the “Q decreasing S-shape” branch on Figure 1), there are much fewer bubbles between the gas bubbles injection ring and the guide vanes than when the S-shape description is performed from the low discharge to the high discharge (#9 and # 10 on Figure 3 as well as the “Q increasing S-shape” branch on Figure 1). From the analysis of the gas bubbles’ evolution, we can note that there is much less backflow close to the hub in the vaneless gap when discharge evolution decreased than when discharge evolution increased.

From optimum operating points and in decreasing discharge in the turbine, the flow field remains almost without disturbance for as long as possible (#1, #2, #3 and #4 on Figure 3) on the hub of the
current model until the moment when backflows suddenly appear (#5 on Figure 3). Once there are too many backflows, these water flow fields keep this structure up to zero discharge. These unsteady backflows can generate strong instabilities. In order to reach flow fields without specific disturbance from these strong backflow structures, it is necessary to increase more discharge (#11 on Figure 3).

**Figure 3.** Flow structures on the hub of the vaneless gap between the runner and the guide vanes

3.4. **Flow structures in the runner inter-blade channels**

The study of the flow field behavior in the runner is detailed. Figure 4 and Figure 5 present pictures at two different locations in the runner inlet (pressure side of blades and at shroud) which were obtained at the same operating points as those shown in Figure 1 and Figure 3. In these images, wires were used to reveal water flow fields at 2 locations (Figure 2). In Figure 4, wires are fixed on the pressure side of the blades (“Wires 1” on Figure 2), halfway up the channel height. In Figure 5, wires are positioned in the middle of the runner shroud (“Wires 2” on Figure 2). Figure 4 and Figure 5 show a change of water flow behaviour in the runner according to the operating points.

It has already been observed in the vaneless gap between the runner and the guide vanes that the flow field does not show any specific disturbance at the optimum operating points (#1 of Figure 4 and
Figure 5). Wires are straight in a narrow cone both on the pressure sides of the blades and on the bottom of the flow channels, in the runner.

Then, for around $n_{\text{ED-Max}}$ operating points ($#2$, $#3$, $#4$, $#5$, $#9$, $#10$, and $#11$ on Figure 4 and Figure 5), at runaway ($#6$ and $#8$ on Figure 4 and Figure 5) and at the zero discharge point ($#7$ of Figure 4 and Figure 5), water entering into the runner is much more disturbed and most of these unstable S-shape points clearly show backflows. On some pictures, the wires are very twisted (examples for points $#7$ on Figure 4 and on Figure 5), perpendicular to the channel (example for point $#2$ on Figure 5), or even directed in the opposite direction of the flow (examples for points $#4$ and $#7$ on Figure 5). The cones in which the wires are located can be very wide (examples for point $#11$ on Figure 4 or point $#5$ on Figure 5). In addition, the water flows structures are different depending on where we look. On the mid-height of the channel at the pressure side of the blades (Figure 4) or at the bottom of the runner shroud (Figure 5), the flow fields are different.

![Figure 4. Flow structures on pressure side of blades at the runner inlet](image)

From the runaway ($#6$ and $#8$ on Figure 4 and on Figure 5) to the zero discharge point ($#7$ on Figure 4 and on Figure 5), the flow fields at the entrance of the runner are very disrupted. This is in accordance with the observations performed in the vaneless gap between the runner and the guide vanes.

Concerning S-shape hysteresis, near the $n_{\text{ED-MAX}}$, different flow structures were observed depending on the S-shape branch being considered. In all observed locations, flow fields on the “Q decreasing S-shape” branch are different than flow fields on “Q increasing S-shape” branch.

When the S-shape curve is described by decreasing the discharge, the water flow field in the volume below the pressure side wire height is disturbed ($#2$, $#3$ and $#4$ on Figure 4). Some wires are perpendicular to the blade side, but overall, no wires are observed going in completely the opposite
On the “Q increasing S-shape” branch, wires take all the place in the channel. In some pictures (#10 and #11 on Figure 4), wires are even seen going in the opposite direction. Flow field structure at this location is therefore clearly not the same depending on the S-shape branch.

If we analyze the wire behaviors at the bottom of the runner, the water flow gradually becomes perpendicular to the blade sides (#2, #3, #4 and #11 on Figure 5). This means that at the bottom of the runner, water circulates in the opposite direction when the S-shape nED-MAX region is described as decreasing the discharge. On the “Q increasing S-shape” branch (#9 and #10 of Figure 5), the flow field does not seem to be disturbed at the bottom of the runner channel inlets with straight and calm wires.

Flow fields in the runner have a different equilibrium in different branches of the S-shape hysteresis. At the upper cross point of the two S-shape branches (#2 and #11 on Figure 4 and on Figure 5), the flow field abruptly changes its structure to find the same structure of the flow field located on the “Q decreasing S-shape” branch. Similarly, at the lower cross point of the two S-shape branches (#5 and #9 on Figure 4 and on Figure 5), the equilibrium of the flow field on the “Q decreasing S-shape” abruptly changes to reach the equilibrium possible at the “Q increasing S-shape” branch.

![Figure 5. Flow structures on the shroud in the runner inlet](image)

Thus, by assembling all previous observations (Figure 5), the undisturbed, high speed and very directional flow field of optimum operating points tends to be restricted in the upper volume of the channels when the S-shape is described in decreasing the discharge. The water cross section is reduced with the appearance of backflows from the middle to the bottom of channels, preventing even flows in the turbine direction in these bottom volumes. The water cross section decreases until the water flow is no longer enough to keep the mass flow. Then the water flow abruptly changes its structure.

In the other direction, on the “Q increasing S-shape” branch, runner channels are filled with backflows which affect the entire volume of these channels. By increasing the discharge, a directional flow field without specific disturbance seems to appear at the bottom of this runner. This non-disrupted
flow field volume will increase until the undisturbed, high speed and very directional flow field suddenly takes control on the all channels, reattaching the flow field to the blades and preventing any backflow on the runner.

These observations in the runner concur with those carried out on the vaneless gap.

![Summary of water flow structures in the S-shape hysteresis](image)

**Figure 6.** Summary of water flow structures in the S-shape hysteresis

4. Hysteresis impact on transient behavior

In the case of a load rejection, the unit speed rises and the discharge decreases, which means the S-shape will be followed in the direction of decreasing discharge. It is then natural to use the corresponding measurement procedure for the transient numerical model. The results for typical manoeuvres are compared here and show the importance of using the correct description (from high discharge to low discharge).

Transient calculations are performed with numerical tools of GE Hydro. A numerical model of a Pumped Storage Plant (PSP) with 2 units sharing a single penstock is used. The two runner S-shape characteristics are generated from the data described in §3, corresponding to the “Q decreasing S-shape”, and to the “Q increasing S-shape” respectively.

The impact of the hysteresis on transient calculations is assessed for simultaneous Quick Shutdown (electrical fault QSD-E) and successive Quick Shutdowns, which can possibly lead to the risk of water column separation. The results are compared in terms of speed and pressure in the spiral case and pressure in the draft tube.

The distributor closes according to a two-step closing law following temporization.

The Main Inlet Valve (MIV) does not close in order to focus on the S-shape influence.

![Distributor closing law](image)

**Figure 7.** Distributor closing law
4.1. Simultaneous quick shutdowns
Both units are initially operating in turbine mode under maximum head and at maximum output. At \( t=10s \), the circuit-breaker opens for both units and the distributor starts to close according to the closing law given in Figure 7. The results are shown on Figure 8. The red curves correspond to the “Q decreasing S-shape” while the blue curves correspond to the “Q increasing S-shape”.

![Figure 8. Comparison between both sides of S-shape hysteresis for a simultaneous quick shutdown pressure in the spiral case (left), unit rotating speed (right)](image)

|                      | Q decreasing S-shape | Q increasing S-shape |
|----------------------|-----------------------|-----------------------|
| maximum spiral case pressure (mwc) | 472.6                 | 463.8                 |
| maximum unit rotating speed (rpm)   | 462.3                 | 456.8                 |

The results are significantly more critical for the “Q decreasing S-shape”.

4.2. Successive quick shutdowns
Both units are initially operating in turbine mode under maximum head and at maximum output. At \( t=10s \), the circuit-breaker of the first unit opens and the distributor starts to close according to the closing law given in Figure 7. At \( t = 12.8s \), the circuit-breaker of the second unit opens. The results are shown on Figure 9.

![Figure 9. Comparison between both sides of S-shape hysteresis for a successive quick shutdown pressure in the draft tube (0mwc=1atm)](image)

|                      | Q decreasing S-shape | Q increasing S-shape |
|----------------------|-----------------------|-----------------------|
| minimum draft tube pressure (mwc) | -4.05                 | 7.12                  |
As for the spiral case pressure and speed in the case of simultaneous quick shutdown, the results are more critical for the “Q decreasing S-shape”, and the risk of water column separation is significantly higher.

5. Conclusion
A hysteresis on the S-shape characteristics was observed during scaled pump-turbine tests. In order to better understand this phenomenon, flow field behavior was studied in a pump-turbine runner and in the vaneless area located between the guide vanes and the runner of a large fixed guide vane opening. A specific device for visualizing the flow field inside the runner was developed in a scaled model of a medium head pump turbine machine. Windows, lights, high resolution cameras and tracers (wires and gas bubbles) were combined to visualize the water behavior.

At the optimum operating points, the flow field does not show any disturbance. However, in the S-shape area, runner inter-blade channels show important backflows. At the zero discharge point, backflows affect the entire volume of these channels.

In the S-shape area, the current study clearly shows a structural difference of flow fields in the pump-turbine runner depending on whether the S-shape is described in increasing or decreasing the discharge. Indeed, two flow field blockages were highlighted. On the one hand, by decreasing the discharge from the optimum point to the runaway, the flow field tends to be restricted in the upper volume of the runner inter-blade channels before it suddenly changes its structure. On the other hand, by increasing the discharge from the runaway to the optimum point, a main flow field without specific disturbance appears progressively, but only at the bottom of the runner, until a direct flow field suddenly takes control on the all channels and prevents any backflow.

These different flow fields have consequences on turbine characteristics and on transient behavior. In the scope of a safety assessment of the worst hydraulic transient manoeuvres, the current results show that the influence of the hysteresis is significant and that the measurements corresponding to the decreasing discharge must be used in the S-shape characteristics. A model based on increasing discharge for the S-shape characteristics leads one to underestimate the risks of pressure and speed transients.

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