Experimental investigation of a free surface oscillation in a model pump-turbine

Anton Maly and Christian Bauer
TU Wien, Institute of Energy Systems and Thermodynamics
Research Unit of Fluid Flow Machinery
Getreidemarkt 9/302, Vienna, AT
E-mail: anton.maly@tuwien.ac.at

Abstract. Hydro power plants provide balancing services to the power grid and the amount is expected to increase in the near future. One of these services is the compensation of reactive power and the regulation of the power factor. Therefore, hydro power units equipped with synchronous machines are operated in so called synchronous condenser mode. During this operation the runner is dewatered and rotates in air above a free surface at the draft tube cone. As a result, a free surface oscillation is excited under some conditions. This paper deals with the experimental investigation of this flow phenomenon. Therefore, model tests are conducted at the hydraulic laboratory of the Institute of Energy Systems and Thermodynamics at TU Wien. The investigated model pump-turbine is equipped with a draft tube cone made of acrylic glass for optical investigations. In addition to the standard instrumentation, fast response pressure transducers are installed at different planes and positions. The machine setup and measurement conditions aim at the investigation of the free surface oscillation and shall prevent other influences. The experiments are performed for both runner rotation directions, different initial water levels at the draft tube and different densimetric Froude numbers. High speed camera recordings are conducted and the amplitude of the water formation is determined by post processing the captured images. In periodic state the frequency of the free surface oscillation is extracted out of the pressure signals. Finally general trends and dependencies are deduced from the acquired data.

1. Introduction
The present paper deals with the experimental investigation of a free surface oscillation in the draft tube of a radial model pump-turbine. This flow phenomenon occurs under some conditions, at which the hydraulic machine is operated with dewatered runner and consequently the runner rotates in air above a free surface. This is the case during operation in synchronous condenser mode as well as in standby and pump start up. In the last years these operation modes, which are mainly caused by grid regulation services, especially the synchronous condenser mode, gain in importance. Driven by policy and environmental protection aspects the power system is forced to undergo structural changes. The European Union aims to reduce the green house gas emission until 2050 by 80 to 90% in reference to the level of 1990 [1]. As a result there is a high need of balancing capacity, storage and grid investments to reach this goal. One of these grid services is the regulation of the power factor. As a synchronous generator is an attractive device for the correction of the power factor, hydro power plants are well suited for that [2].
A significant quantity regarding investigations of free water surface flow in the draft tube of a hydraulic machine is the densimetric Froude number $F_d$. This dimensionless number was first introduced in [3] and is the ratio of kinetic energy to potential energy. It concerns the interaction between air and water surface in dependence on the density of the fluids and the runner speed. [4] confirms and reinforces the use of $F_d$ as dimensionless number for investigations regarding the free water surface in the draft tube cone.

The definitions provided in literature slightly differ. These differences in definition of this dimensionless key figure should be explicitly noticed and are described in detail in [5]. The densimetric Froude number $F_d$ is hereinafter defined as

$$F_d = \sqrt{\frac{\rho_A}{\rho_W} \frac{u_2}{g D_2}}$$  

with the density of air $\rho_A$ and water $\rho_W$, the constant of gravity $g$, low pressure side diameter of the runner $D_2$ and $u_2$ the circumferential velocity of the runner at diameter $D_2$. As the densities are a function of pressure and temperature, $F_d$ also depends on these parameters.

2. Experimental setup

The model tests are performed on a test rig located at the Laboratory of Fluid Flow Machinery at the TU Wien. Investigated model pump-turbine has a specific speed factor $N_{QE} = 0.126$ ($n_q = 41.8$ rpm) in turbine mode and $N_{QE} = 0.125$ ($n_q = 41.6$ rpm) in pump mode. $N_{QE}$ is defined according IEC 60193 [6]. The runner consists of seven runner blades and the scale reduced radial pump-turbine is equipped with 20 guide vanes and 20 stay vanes. The main parts of the model machine as well as fluidic connections and initial conditions are illustrated in Figure 1.

![Figure 1](image_url) Cross section view of the investigated model pump-turbine - Initial conditions of water volume and fluidic connections
A spherical valve is arranged upstream of the headwater side in the spiral case inlet pipe to simulate start, stop or shut down conditions. The spiral case is connected with the draft tube by a connection pipe for pressure equalisation similar to spiral case pressure relief. It can be disconnected by a shut off valve. The experimental setup aim at the investigation of the free surface oscillation and shall prevent other influences. In order to avoid hydraulic flow phenomena at the high pressure side, the spiral case is dewatered. As a result there is no water ring as appearing in synchronous condenser mode of the prototype [7], [8] and no cooling discharge through the labyrinth sealing as this may cause torque fluctuations [9]. Similar to prototype machines the guide vanes are closed. The headwater sided spherical valve is closed too and there is no connection to the headwater vessel filled up with water. In contrast to [3] and [4] the draft tube is connected to the tailwater vessel as usually. A blind plate is not set at the tailrace.

Figure 2. Simplified representation of draft tube cone region at initial state with initial waterlevel $\kappa$

Figure 3. Simplified representation of the free surface oscillation, illustration of coordinate system and important terms

At initial conditions the entire test rig, water mass and free surface are at rest. A simplified representation of the draft tube region at initial state is shown in Figure 2. At these conditions the water surface is below the runner low pressure side. The vertical distance from the runner low pressure side to the water surface is given as a multiple of $D_2$ by $\kappa$. Consequently, the investigated initial water levels are named $\kappa$. As illustrated in Figure 3 the amplitude of free surface oscillation is defined relative to $\kappa$. The vertical elongation of the water surface is named $z_{FSO}$ with belonging coordinate origin at the intersection of runner low pressure side and rotational axis.

Investigated model machine is equipped with pressure transducers used for steady measurements and fast responding piezoresistive pressure transducers used for unsteady measurements. Six pressure measurement sections are instrumented with fast response pressure transducers. The measuring points in each section are arranged as suggested by [10]. The whole instrumentation of the test rig and the test rig itself are presented in detail in [11].
A schema of the high speed camera arrangement and the data acquisition chain is illustrated in Figure 5. The optical axis of the camera is at an angle of 30 degrees to the draft tube symmetry plane. The high speed camera focuses on the front inner draft tube surface. It is used to monitor the behaviour of the water surface. In order to determine the vertical elongation of the free surface oscillation the captured images are post-processed. First, a coordinate system is superimposed on the images and the region of interest (ROI) is defined. Once the edge of water surface is specified, images are processed subsequently. Vertical movement of the edge is detected along the projection of the center line as illustrated in Figure 4. The z-coordinate of the tracked point is saved in pixel units for every image. In the last step they are converted by means of the scaling factor known from in situ calibration.

Image acquisition of the high speed camera and unsteady pressure measurements are started synchronously by a TTL signal. During the high speed recording the general operation parameters are measured as well; time resolved and mean values. Data collection of general operation parameters starts 10 seconds before high speed recording. General measurement procedure of one test series depends on the state of the free water surface in the draft tube. The initial conditions were described previously and are shown in Figure 1. After the machine start up from initial conditions there are two possibilities:
• Either the water surface stays flat during the entire time of 30 minutes. If that is the case one recording is done and the densimetric Froude number $Fd$ is increased by increasing the runner speed.

• Or a motion of the fluid in runner rotation axis (vertical direction) is observed. In this case one recording is performed after the oscillation reaches a periodic state. A free surface oscillation is defined as periodic, if no changes in amplitude and oscillation mode are observed for a period of 60 seconds. After a waiting time of five minutes a second recording is done to confirm periodic state. In the next step $Fd$ is increased.

![Diagram](image)

**Figure 5.** Schema of the data acquisition chain and the high speed camera arrangement

3. Results
The model tests are executed for densimetric Froude numbers $0 \leq |Fd| < 0.5$ with the runner rotating in pump as well as in turbine rotation direction for three initial water levels: $\kappa = 0.25$, 0.50 and 1.00. Whereby $\kappa = 1.00$ is the lowest water level with biggest distance to the runner low pressure side and $\kappa = 0.25$ highest water level with the smallest gap between free surface and runner. All test series show the same qualitative behaviour of free surface depending on the densimetric Froude number $Fd$. It can be roughly categorised into 3 stages:

First for small $Fd$ no significant elevation of the water surface is observed. The free surface is in rotation, but stays mainly flat. Only very small waves appear apparently chaotic at the circumference. With increasing $Fd$ this behaviour is followed by a small transition range. In the end, free surface oscillation reaches its final periodic state with azimuthal wave number $m = 1$, which was also observed in [3] and [4]. The rotation direction of the runner and free surface oscillation are the same. As a result of the test series a critical densimetric Froude number $Fd_{crit}$...
is identified. If $|Fd| > Fd_{crit}$ a free surface oscillation occurs for both runner rotation directions and all initial water levels. Subsequently presented results are detected at final periodic state.

![Figure 6](image_url)

**Figure 6.** Signal of free surface oscillation ($Tu - \kappa = 0.50; Fd = 0.214$)

In Figure 6 the detected motion of the free water surface at the circumference is depicted for runner rotating in turbine rotation direction at $Fd = 0.214$ with an initial water level $\kappa = 0.50$. The motion of free water surface is detected by means of captured high speed camera recordings and post processing as explained in detail in [5]. The vertical elongation of the free surface oscillation $z_{FSO}$ is normalized by $D_2$ and plotted in time domain. $z_{FSO}/D_2 = 0$ matches the runner low pressure side and the red continuous horizontal line marks the initial water level. As one can see, the free surface oscillation is periodic. In reference to the initial water level an asymmetry of the propagation in vertical direction is clearly recognizable. The increase of water due to the free surface oscillation is bigger than the decrease. Thereby troughs are wider than the peaks. This is expected to be caused by the conical shape of the draft tube and centrifugal forces due to the rotation of water mass.

The amplitude and the maximal level reached by free surface oscillation are extracted out of the captured signals for the three initial water levels. The highest amplitudes are detected when the initial water level is set to $\kappa = 1.00$. Generally, a slight difference in amplitude depending on the runner rotation direction is observed. If the runner rotates in pump rotation direction the amplitudes are slightly higher. The absolute vertical elongation of the free surface oscillation $z_{FSO}$ as well as the distance of the water surface to the runner low pressure side depends on both, the amplitude of the free surface oscillation and the initial water level. Each point presented in Figure 7 is a mean value of all detected peaks for one initial water level, one runner rotation direction and $|Fd| > Fd_{crit}$. The error bars indicate the standard deviation of these values. Black line refers to turbine rotation direction and red line to pump rotation direction. The mean values correlate with the initial water level. In a rough approximation the distance between runner and free water surface is half of the distance between runner and initial water level. The amplitude of the free surface oscillation decreases with decreasing $\kappa$. A contact between the free surface and the rotating runner can not be identified. However, for same $Fd$ the breakaway of water droplets increases with decreasing $\kappa$ and especially at an initial water level of $\kappa = 0.25$ the free surface is ruptured, resulting in large amounts of splash water and spray to be sucked into the runner.
In addition to the vertical elongation, also the rotational frequency of the free surface oscillation $f_{FSO}$ is investigated. It is determined by means of the pressure transducers installed at the draft tube cone. A comparison of the optically captured surface motion and two exemplary pressure signals is illustrated in Figure 8. All signals are plotted in time domain. Again, the vertical elongation of the free surface oscillation is normalized by the runner low pressure side diameter $D_2$. The pressure signals are normalized by the signal mean value $p_{mean}$. The frequency of the optically determined signal correlates to the frequency of both signals detected by the pressure transducers. This proves that the pressure signal is well suited to clearly determine $f_{FSO}$. The time offset of the pressure signals and vertical elongation signal of the free surface oscillation is caused by the angular offset between the optical and the pressure measuring axis.

Figure 8. Pressure signals at $\kappa = 0.25$ (blue) and $\kappa = 0.75$ (red) compared with elongation of free surface oscillation
The frequency of free surface oscillation in final periodic state (azimuthal wave number $m = 1$) is determined by analysing the pressure signals using the Fast Fourier Transformation. A normalized frequency spectrum of the pressure signals for runner rotating in turbine rotation direction, $Fd = 0.214$ and initial water level $\kappa = 0.50$ is shown in Figure 9.

![Normalized frequency spectrum of pressure signals](image)

**Figure 9.** Normalized frequency spectrum of pressure signals ($Tu - \kappa = 0.50; Fd = 0.214$)

Depicted frequency spectrum has a dominant peak at $f = 1.90 Hz$. This peak is caused by the rotational motion of the free surface oscillation. It is detected on all pressure transducers. Other noted peaks at higher frequencies are harmonic ones. The first harmonic reaches an amount of approximately $0.3A_{max}$ and higher harmonics reach less than $0.1A_{max}$.

The frequencies $f_{FSO}$ of the detected peaks are plotted against the densimetric Froude number $Fd$ in Figure 10. Negative $Fd$ indicates the runner and the accompanying free surface oscillation to be rotating in pump rotation direction. Vice versa a positive $Fd$ indicates a rotation in turbine direction. In general the frequency of the free surface oscillation increases with increasing $|Fd|$. The air flow, driven by the runner, accelerates the water mass due to shear stresses at the boundary layers of the fluids. The main air flow is rotating and due to centrifugal forces secondary flow appears as described in [12]. For $Fd < 0$ the gradients of the regression lines are greater than those of the corresponding regression lines for $Fd > 0$ at the same initial water level. The regression lines for the same initial water level meet at $Fd = 0$. The frequencies of these theoretical intersection points of the regression lines and the ordinate become higher the lower the distance between the runner and initial water level is. The absolute values of the gradients of the regression lines show a contrary trend and decrease with increasing initial water level. The intersection points in Figure 10 are independent of the runner rotation direction and only depend on the initial water level $\kappa$. Due to this result these values are considered as only geometry dependent.

In a first physical interpretation it is assumed that the observed increase of the rotational frequency is caused by an increase of the angular velocity of the local water mass in the draft tube. This rotating water mass is interpreted as rotating frame of reference. The motion of the free surface is interpreted as relative motion belonging to the frame of reference. Its relative frequency is constant and does not increase as it is only geometry dependent. This is depicted by the intersection points of the regression lines and the ordinate in Figure 10. The water
mass, which is interpreted as frame of reference, is driven by the air flow. The air flow itself is driven by the runner. Therefore the increase of $f_{FSO}$ is assumed to be caused by an increase of transmitted torque. This approach explains why the gradients of regression lines are higher for $Fd < 0$. Although the runner is not designed for operation in air, the torque transmission is higher for runner rotating in pump rotation direction. Hence, the transmitted torque at the surface increases and the water is driven at higher speed. Therefore the gradient of the regression lines depend on the transmitted torque.

4. Conclusion
The flow phenomenon is observed by means of high speed camera recordings. The qualitative behaviour of the free surface is recorded and the distance to the runner low pressure side in final periodic state with azimuthal wave number $m = 1$ is determined. It is observed that the distance between runner and free water surface correlates to the initial water level. In a rough approximation it is half of the distance between runner and initial water level. This is caused by a decrease of the amplitude of the free surface oscillation. The breakaway of water droplets increase with decreasing distance to the runner.

Unsteady pressure measurements are performed at different draft tube cone regions and the frequency of the free surface oscillation $f_{FSO}$ is determined by the means of the pressure signals. The detected frequency of the free surface oscillation increases with increasing $|Fd|$. The characteristic can be described by a linear function and the intercept depends only on geometrical parameters. The gradient of the regression line depends on the runner rotation direction and $Fd$. These findings are motivation for a future analytical approach basing on the physical interpretation.
Acknowledgments
The authors would like to thank the Research Unit of Numerical Fluid Mechanics of the Institute of Fluid Mechanics and Heat Transfer for providing the high speed camera used for the investigations.

References
[1] European Commission 2012 Energy Roadmap 2050
[2] Hendry M L and McGough J C 1995 Synchronous Condensing Using the Generator of Peak Load Plant Proc. ASME 1995 Int. Gas Turbine and Aeroengineering Cong. and Exp.
[3] Tanaka H, Matsumoto K, and Yamamoto K 1994 Sloshing motion of the depressed water in the draft tube in dewatered operation of high head pump turbines XVII IAHR Symp. pp 121-130
[4] Vagnoni E, Arthur F, Andolfatto L, and Avellan F 2018 Experimental investigation of the sloshing motion of the water free surface in the draft tube of a Francis turbine operating in synchronous condenser mode Exp. Fluids 59 95
[5] Maly A 2019 Experimental Investigation of Free Surface Oscillation in the Draft Tube of Hydraulic Machines
[6] International Electrotechnical Commission 1999 IEC 60193: Hydraulic turbines, storage pumps and pump-turbines – Model acceptance tests
[7] Zanetti V and Rossi G 1978 Synchronous condenser operation and running up in air of a medium characteristic speed pump-turbine: model tests IX IAHR Joint Symp. on Design and Operation of Fluid Machinery pp 337-352
[8] Ceravola O, Fanelli M, and Lazzaro B 1980 The behaviour of the free level below the runner of Francis turbines and pump-turbines in operation as synchronous condenser IAHR Symp. pp 765-775
[9] Vagnoni E, Andolfatto L, Guillaume R, Leroy P and Avellan F 2018 Air-Water Ring in the Vaneless Gap of a Reversible Pump-Turbine Operating in Condenser Mode Proc. 10th Int. Symp. on Cavitation (ASME Press)
[10] Kuschel M and Seume J 2011 Influence of Unsteady Turbine Flow on the Performance of an Exhaust Diffuser Proc. ASME 2011 Turbo Exp.: Turbine Technical Conf. and Exp.
[11] Maly A, Käfer K and Bauer Ch 2019 Flow phenomena in a model pump turbine at synchronous condenser mode – description of test rig Wasserwirtschaft S1
[12] Steinrück H and Maly A 2018 A rotary wave in phase condenser mode Proc. Conf. on Modelling Fluid Flow pp 1-8