Pressure pulsations during a fast transition from pump to turbine mode of operation in laboratory and field experiment

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Abstract. The reversible pump turbine (RPT) is a suitable machine to meet fluctuations in the energy market. The usage of RPTs for this purpose will increase the number of operational mode changes of the machine. In order to reduce the response time of the machine, fast transitions in the mode of operation are desired. Therefore, increased knowledge of how the machine operates during these fast transitions is needed. This paper presents measurements done both at the NTNU Waterpower Laboratory and Tevla Pump Power Plant. The two machines are not geometrically similar, and part of the result focus on the similarities in the measurements despite the differences in the two RPTs. Tevla is owned by the Norwegian company Nord-Trøndelag Energi (NTE) and consists of two reversible pump turbines. The installed capacity is 50 MW. The focus is on the pressure pulsations during the fast transition from pump to turbine mode of operation. Results from both the laboratory and field measurements show few but high pressure amplitudes during the fast transition.

1. Introduction
Balancing the fluctuations in the energy market, especially after the introduction of intermittent energy sources, are an important challenge. The reversible pump turbine (RPT) can be used to meet these fluctuations. To effectively use the RPT in this manner, the machine will experience an increase in the number of operational mode changes. In order to reduce the response time of the machine, fast transitions between the modes of operation are desired. How these fast transitions change the pressure pulsations experienced by the machine and penstock is important to know when evaluating a possible procedure change for the transition between pump and turbine mode of operation.

This article presents pressure measurements from the transient change from pump to turbine mode of operation. Results from both laboratory and full scale power plant test are shown and compared, even though the two cases are different not only in size, but also have different runner geometry, guide vane design and penstock. The focus is on the pressure pulsations during the fast transition from pump to turbine mode of operation.

The pressure pulsations in RPTs in off-design operation is a well researched area exemplified by Zuo et. al [1] in their review of pressure pulsations in vaneless space of a high head pump turbine. The most prominent pressure pulsations causing fatigue come from rotor stator interaction (RSI) and pressure pulsations that corresponds to the natural frequency (NF) of the
machine. In a transient operation the stochastic pressure pulsations (SPP) tend to be dominant \cite{2}. With a highly transient phenomena like a fast mode change, there will be no time for the pressure pulsations that correspond to the natural frequency to develop any resonance. It is therefore most relevant to focus on the amplitudes themselves, rather than finding the natural frequency.

Braun and Ruchonnet \cite{3} are among the few who have extended the research of pressure pulsations on to the area of operational mode transitions. In the laboratory experiments they did a number of transitions from pump to turbine mode of operation with different speeds. Their results indicate that the intensity of the pressure fluctuations in fact decreases with increased speed.

2. Method

The experiments presented in this article were conducted at the Waterpower Laboratory at NTNU and at Tevla pump power plant (Tevla). Tevla is a power plant with two reversible pump turbines (RPT) and an installed capacity of $2 \cdot 25$ MW. Tevla is located in Nord-Trøndelag in Norway, and is owned by Nord-Trøndelag Energi (NTE).

The two turbines are not geometrically similar, as can be seen from their respective specific speeds ($N_{QE}$) in Table 1 and Table 3. The results presented are thus not a comparison of a model with its prototype.

The area of investigation is the fast transition (FT) from pump to turbine mode of operation and the following pressure pulsations of this transition. The fast transition from pump to turbine start in normal pump mode of operation, where the wicket gate opening is reduced from optimal pump opening to a reduced opening. After the adjustment of the guide vanes, the connection between the generator/motor and the RPT is disconnected, in the same manner as in a load rejection scenario. Because of the pressure from the water masses the RPT will go from pump mode to runaway speed in turbine mode, and in the process traveling through pump break mode. At the same time, the wicket gate is kept open and constant in the reduced opening to avoid high runaway speed.

In the laboratory, it was not possible to reduce the wicket gate opening to the degree where the rotational speed corresponds to 50 Hz. The method was therefore carried out for a number of different guide vanes openings; $4^\circ$, $7^\circ$ and $10^\circ$. At Tevla, the reduced wicket gate opening corresponds to $\alpha_{idle}$, the opening that gives nominal speed at runaway in turbine mode of operation, i.e the opening degree for turbine start up. The RPT therefore ends up at the ideal position to reconnect the generator and connect the machine to the grid. The method was first tested in the laboratory, and later carried out at Tevla. The only difference was the reduced wicket gate opening.

2.1. Laboratory tests

When doing transient experiments it is important to remove disturbances on the system caused by the pump supplying the head. The Francis test rig was therefore arranged to operate in an open loop configuration. In order to disconnect the hydraulic inertia of the outlet system a weir was installed in the outlet tank. The laboratory set-up was the same as used by Eve Walseth \cite{4}. Figure 1 show the sensor placements in the test rig and Table 2 show the instrument parameters, and have a sampling rate of 5000 Hz.

The model runner is designed by Grunde Olimstad \cite{5} during his PhD work. The runner parameters from a turbine perspective are listed in Table 1 and in accordance with IEC 60193 \cite[p. 26]{6} 1 is the high pressure side, and 2 is the low pressure side.
Figure 1. Sensor placement laboratory measurements.

Table 1. RPT - turbine properties.

| $D_1$ | $D_2$ | $B_1$ | $n_{ED}^*$ | $Q_{ED}^*$ | $H^*$ | $\beta_1$ | $\beta_2$ | $\alpha^*$ | $N_{QE}$ |
|-------|-------|-------|------------|------------|-------|-----------|-----------|-----------|---------|
| 0.631 m | 0.349 m | 0.059 m | 0.133 | 0.223 | 29.3 m | 12$^\circ$ | 12.8$^\circ$ | 10$^\circ$ | 0.0628 |

Table 2. Laboratory sensor parameters.

| Sensor | Type           | Range | Precision |
|--------|----------------|-------|-----------|
| $p_{2l}$ | UNIK 5000 | 10 bar | 0.1%      |
| $p_{3l}$ | Kulite XTE190 | 7 bar | 0.5%      |
| $p_{4l}$ | Kulite XTE190 | 7 bar | 0.5%      |
| $p_{5l}$ | UNIK 5000 | 5 bar | 0.1%      |

2.2. Tevla tests

One of the turbines was used in the test presented. During the experiment the other turbine was at standstill with the main inlet valve closed. The execution of the fast transition required an operation of the power plant outside of normal procedures. A number of protection systems were shut off so as not to trigger the normal shutdown procedure if the power plant experience a load rejection. Then the control system was turned to manual and the wicket gates were manually adjusted to to $\alpha_{idle}$. Finally the main circuit breaker was turned, disconnecting the generator from the grid and leading to the fast transition. Due to the complexity of a modern power plant, a number of attempts were needed to find the correct method to bypass the fail-safes in the system. The end result was therefore one successful completion of the fast transition.

Table 3. Tevla parameters.

| $P$ | $\alpha^*$ | $\alpha_{idle}$ | $H_{net}$ | $N_{QE}$ |
|-----|------------|-----------------|-----------|---------|
| 25 MW | 53.9% | 14.7% | 148.4 m | 0.126 |

The sensor placement at Tevla was decided by existing pressure taps. The difference from the laboratory setup were the lack of pressure measurements in the vaneless space. Instead two...
pressure taps at the spiral casing was accessible. The position of the pressure sensors are shown in Figure 2 and the instrument parameters can be seen in Table 4.

| Sensor  | Type      | Range | Precision |
|---------|-----------|-------|-----------|
| $p_{3f}$ | UNIK 5000 | 50 bar | 0.1%      |
| $p_{4f}$ | UNIK 5000 | 10 bar | 0.1%      |
| $p_{5f}$ | UNIK 5000 | 50 bar | 0.1%      |
| $p_{6f}$ | UNIK 5000 | 100 bar| 0.1%      |

2.3. Data processing

The Rainflow counting method is commonly used for cycle counting in fatigue analysis [2]. The principle can be used just as well to analyze pressure amplitudes. When doing transient measurements where the pressure pulsations are stochastic, the use of Fast Fourier Transform (FFT) is inconvenient, since the pulsations doesn’t occur at certain frequencies. Using the pressure measurements together with the sample rate of 5000 Hz with the Rainflow method gives the amplitude of the pressure pulsations together with the number of cycles each amplitude occurs. The Rainflow method is described in the standard ISO 12110 [7].

When analyzing the pressure pulsations from both the laboratory and the field measurements, the lowest amplitudes have been disregarded. The area of interest are on the pressure amplitudes outside the ranges found during normal operation. In both cases, pressure pulsations measured at Best Efficiency Point (BEP) in turbine mode of operation have been used as the basis for this low amplitude threshold.

3. Results and Discussion

The fast transition start at steady state pump operation, marked in Figure 3 by $A'$. When the generator is disconnected the RPT gradually decreases in flow rate and rotational speed through quadrant $A$. The flow rate changes direction first, and the RPT enters quadrant $B$, the pump break mode. In quadrant $B$ the rotational speed is still in the pump direction, but the flow is now going downstream, as in turbine mode of operation. When the rotational speed reaches zero and starts to accelerate the RPT is in quadrant $C$, turbine mode of operation. The next steady state condition is the runaway speed in turbine mode of operation. The measured pressure pulsations are shown in the subsections for the laboratory and field measurements respectively. Figure 4 and Figure 6 show the rated amplitude of each pressure pulsation with respect to time for laboratory and field measurements respectively. The figures also have numbering explaining
where in the characteristics plot the different amplitudes occur. The rated amplitude \( A_R \) [%], is defined in Equation (1).

\[
A_R = \frac{Amp}{H_{net}} \cdot 100 \tag{1}
\]

Where \( Amp \) is the amplitude of the pressure pulsations and \( H_{net} \) is the head at optimal turbine operation. From the Rainflow method the minimum and maximum amplitudes for each pressure sensor have been found. All the amplitudes have been divided into ten sections presented by its average as the x-axis in Figure 5 and Figure 7 for laboratory and field tests respectively. The ten amplitude sections have a range \( \Delta R \) from displayed average value by ±5 % of the maximum amplitude.

### 3.1. Laboratory measurements

In the laboratory experiment the transition took approximately 8 s and is similar for the different wicket gate openings. As can be seen in Figure 4 the trend in the pressure amplitudes are also the same. The highest amplitudes are found in pump break mode (Section 3) and in the beginning of turbine mode of operation. In Figure 4, section 1 is the period before the fast transition, i.e the steady state pump operation. In section 2, ranging from the start of transient period to the beginning of pump break mode, the increase in amplitudes are first seen at the end of the section. Section 4 is in turbine mode of operation from \( n_{ED} = 0 \) to when \( Q_{ED} \) reaches maximum value. Section 5 is from \( Q_{ED} \) maximum to \( n_{ED} \) maximum. Section 6 is runaway speed. The amplitude magnitude have the same trend with respect to time for all the pressure sensors, even though the ranges differ. The highest amplitudes can be seen in the vaneless space by sensor \( p_{3l} \) and \( p_{4l} \). The lowest amplitude is found by the outlet sensor \( p_{5l} \).
Figure 4. The rated amplitude ($A_R$) for pressure sensors during the fast transition in laboratory. The position of $p_{2l}$, $p_{5l}$, $p_{3l}$ and $p_{4l}$ can be seen in Figure [1].
Figure 5. The number of cycles for all amplitudes ($A_R$) during the fast transition in laboratory. $\Delta R$ is 0.93, 0.53, 1.38 and 1.47 respectively for $p_{2l}$, $p_{5l}$, $p_{3l}$ and $p_{4l}$. 
Figure 6. The rated amplitude ($A_R$) for pressure sensors during the fast transition at Tevla. The position of $p_{3f}$, $p_{4f}$, $p_{5f}$ and $p_{6f}$ can be seen in Figure 2.
Figure 7. The number of cycles for all amplitudes ($A_R$) during the fast transition at Tevla. $\Delta R$ is 0.92, 0.52, 1.38 and 1.46 respectively for $p_{3f}$, $p_{4f}$, $p_{5f}$ and $p_{6f}$. 
Figure 5 shows the summation of all the pressure amplitude cycles for the three different wicket gate openings. All of the results show a high number of small amplitudes. The number of cycles decreases with increasing mean amplitude. The highest wicket gate opening of 10° have the smallest number of high amplitudes for all pressure sensors. In the mid range area the increase in wicket gate opening results in a higher number cycles in the vaneless space.

3.2. Field measurements
The field measurements start at optimal wicket gate opening in pump mode of operation and are first reduced to $\alpha_{idle}$, marked by the start of section 2 in Figure 6. The beginning of section 3 marks the start of the fast transition. Section 3 includes both pump and pump break mode of operation and the maximum amplitudes are in this area. The start of section 4 also have high amplitudes. Section 4 is the turbine mode of operation from $n_{ED} = 0$ to when $n_{ED}$ reaches maximum value. Section 5 is runaway speed. The fast transition at Tevla took 43 s. The sensors closest to the runner show the highest amplitudes. The maximum amplitudes in Figure 7 are few, including the top two columns none exceeds ten cycles.

3.3. Comparison
For both the laboratory and field experiment the results show similar trends. In both cases the hydraulic pressure is the driving force for the fast transition, the subsequent rotational speed and velocity components of the flow causes the pressure pulsations. For all RPTs, even with different specific speed, the operating points with unfavorable flow conditions will cause the higher pressure pulsations. The pressure amplitudes are highest in pump break mode but consists of few number of cycles. Most pressure sensors have one cycle at the highest pressure amplitude and none of the pressure sensor have more than four cycles for the highest amplitudes. The highest relative amplitudes in the laboratory experiment are as high as 71.8%. For the measurements at Tevla the highest relative amplitudes are 29.3%. Since the pressure is measured at two different places with respect to the turbine runner this does not mean that the fast transition at Tevla necessarily experience lower relative pressure amplitudes.

4. Conclusion
The fast transition from pump to turbine mode of operation was successfully conducted both in the laboratory and at Tevla. The laboratory test rig and power plant are different not only in size, but also have different runner geometry, guide vane design and penstock. With all of these differences, the comparison between the two experiments nevertheless show clear similarities. The highest pressure amplitudes occur in the pump break mode. The high amplitudes experienced in this area is the most relevant objection against this method of changing from pump to turbine mode of operation. The pump break mode is an area not entered during a normal start and stop, neither in pump or turbine mode of operation.

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