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Numerical modeling of the pressure signatures from a cracked blade

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Objective

The aim of this study was to develop a high-fidelity numerical model of a Francis turbine with low-specific-speed featuring a typical blade damage, with the intention to explore the flow characteristics that arise due to the damage within the turbine. To achieve this, a transient simulation of the entire Francis-99 model turbine have been performed and data was collected over seven complete revolutions. These results offer valuable insights into the underlying physical mechanisms responsible for the pressure signatures observed during the operation of a turbine with a damaged blade. The findings can contribute to the development of improved methods for monitoring and detecting such structural failures at an early stage.

Background

Frequent and prolonged off-design operation of Francis turbines can increase the fatigue load on the turbine blades. If the structure vibrates significantly, any microscopic material defect will initiate cracks that are growing from the cyclic loads, and eventually lead to blade damage. In recent years, both new and old Francis runners have experienced problems with cracks due to increased grid regulation requirements and market shift, which triggered an increased development of methods for monitoring and early detection of the material fault.

In a previous study conducted at the Waterpower laboratory at NTNU [1, 2], a typical fault occurring on a Francis model runner was experimentally investigated during operation. A crack-like damage was manually created in few stages on one of the blades, at a typical location close to the trailing edge, and the measurements showed that the formation of the crack could not be easily detected until a full fragment was cut out of the blade. Once the fragment was removed, the efficiency of the turbine remained intact, or within the uncertainty of the test rig, but a change in the pressure signature was observed that could not be explained from the collected data. Local flow effects in the channel and a redistribution of the loads of the damaged blade were hypothesized, but without any solid evidence. The development of the crack was done in several steps, as shown on Figure 1, and in this study Case-8 was selected for further numerical investigations.

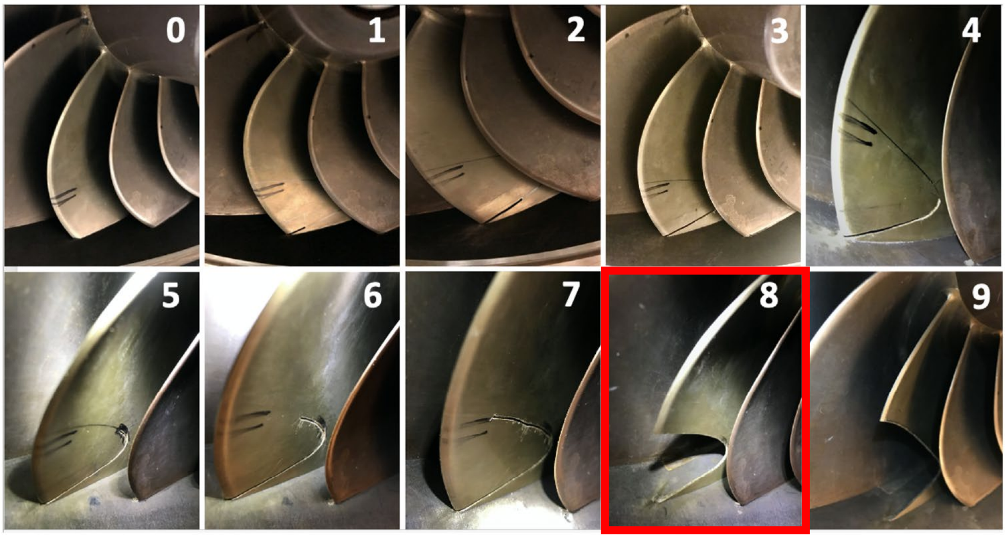

Figure 1. Systematic development of the crack that was subject of previous experimental study at NTNU [1, 2]. Marked is the Case-8 that was used in the detailed numerical simulation presented in the report.

In the present study, the flow conditions were modeled numerically to investigate further the pressure signatures and provide a more detailed picture of the physical mechanism. The geometry consists of the full distributor, the complete runner with 15 main and 15 splitter blades, of which one full-length blade has the damage, and the entire draft tube. On Figure 2 shown is the entire turbine with the locations of the sensors that were used in the experiments, together with a view from outlet of the runner showing the damaged trailing edge of the blade. At the inlet of the domain a total pressure boundary condition was prescribed, while at the outlet of the domain an Opening/Entrainment with static pressure was used. This combination of boundary conditions defines the net head of the turbine, while the discharge is a result of the simulation and is allowed to have fluctuations. The computational grid was generated using both *ICEM-CFD* and *TurboGrid* software packages by ANSYS. The grid description and sizes are given in Table 1.

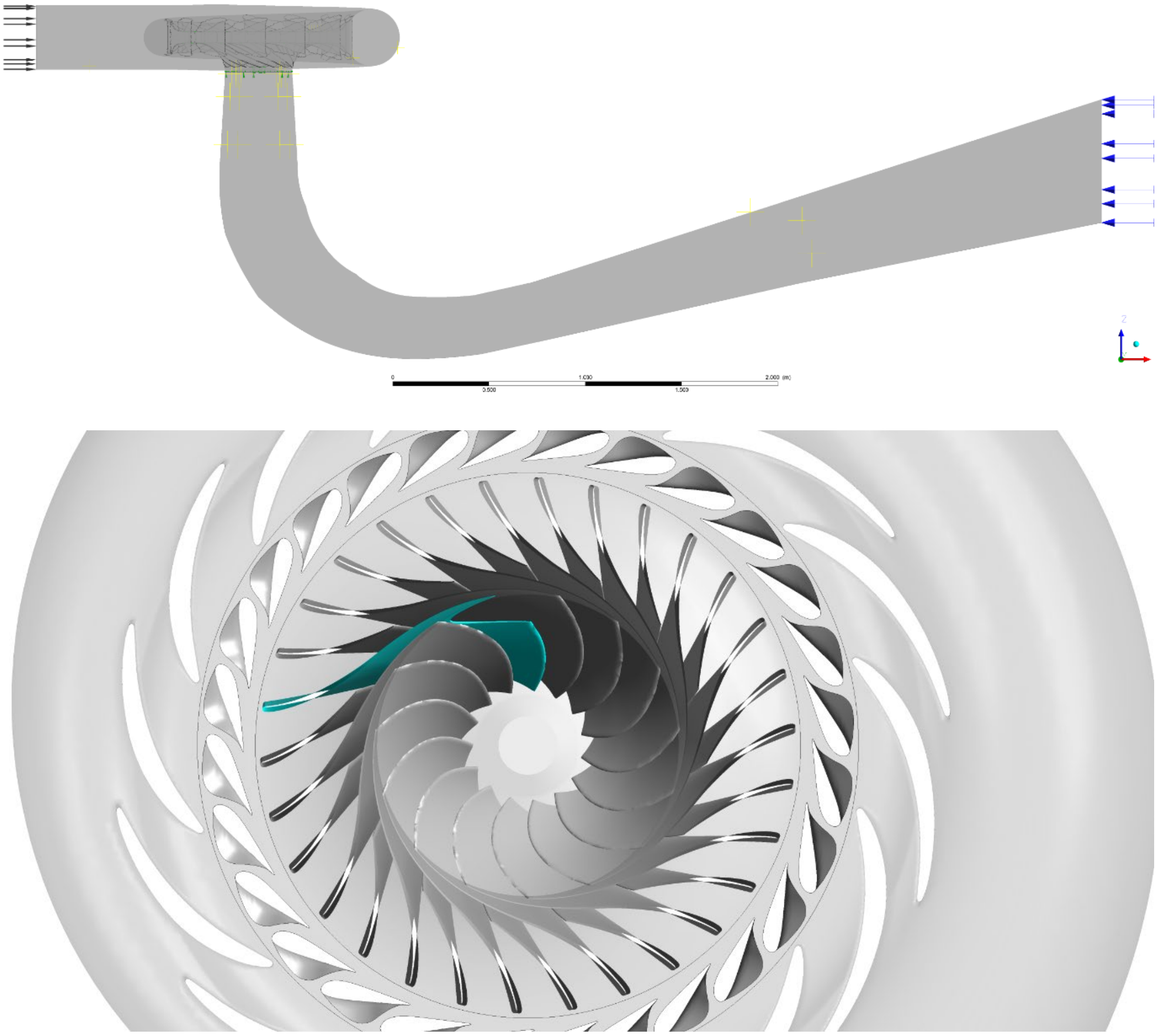

Figure 2. Top figure – the computational domain of the entire turbine, Bottom figure – A view of the open runner from the outlet of the runner showing the damaged blade in cyan color.

Table 1. Size of the mesh for the different domains of the grid

Computational domain	**Number and type of mesh elements**
Spiral Casing + Stay Vanes	2.4M Tetrahedral
Guide Vanes	0.9M Hexahedral
Runner	4.9M Tetrahedral
Draft tube	1.1M Hexahedral
Entire turbine	**9.3M**

Results/Findings

Apart from the monitoring points that were used to extract transient data from the locations of the pressure sensors in the distributor and the draft tube, additional control surfaces were used inside every guide vane channel and every runner channel after the splitter blades. In the postprocessing steps, the volumetric discharge through these control surfaces was extracted for every time step and correlated with the circumferential position of the damaged blade. Figure 3 shows the control surfaces in the runner and guide vanes colored in red. For better visualization, only a few of the runner blades and guide vanes are shown.

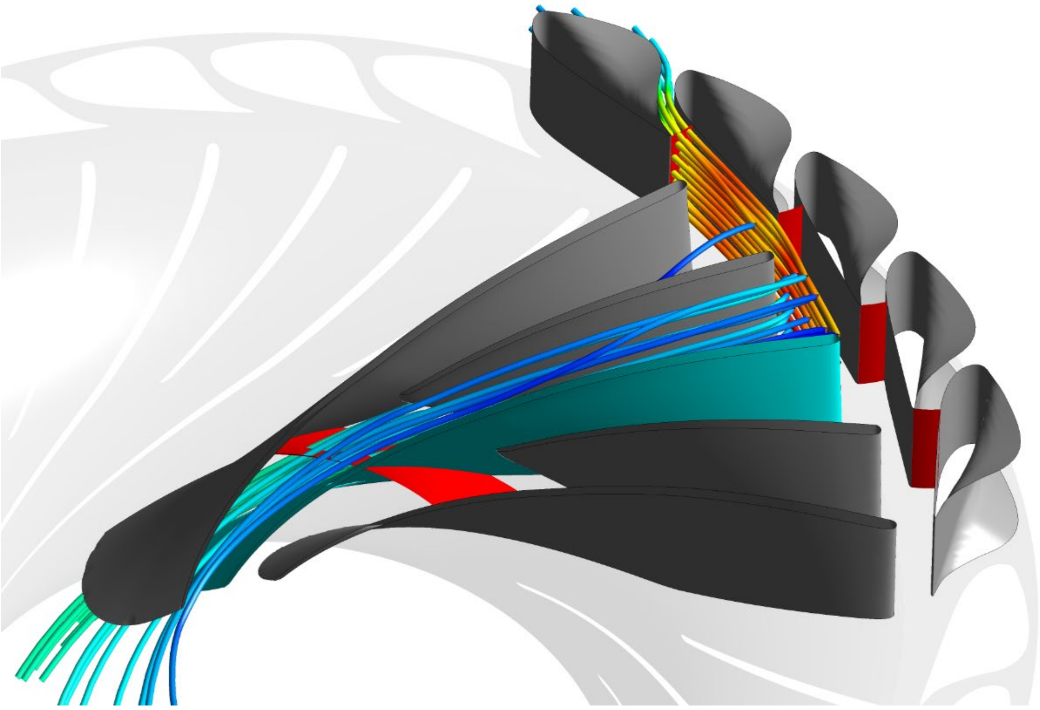

Figure 3. Top figure – the computational domain of the entire turbine, Bottom figure – A view of the open runner from the outlet of the runner showing the damaged blade in cyan color.

Overall, the results from the detailed simulation have revealed two main findings that provide a physical explanation for the measured pressure signatures in the experiments:

1. The damaged blade will influence the adjacent main blade that is facing the pressure side of the damaged blade, which will experience an additional pressure reduction on the suction side and increase of the blade loading throughout the entire blade length. The other neighboring blade facing the suction side of the damaged blade is not affected and the pressure field remains similar to the blades far away from the damaged blade . The local increase of the blade loading for one of the adjacent main blades creates a pressure pulse that is seen in the draft tube sensors with a frequency equal to the rotational frequency of the runner. Figure 4 shows the blade loading for both adjacent blades. Figure 5 shows the pressure contours on the suction side of the blades, while Figure 6 shows the pressure distortion caused by the damaged blade in the blade-to-blade plane at the span where the blade damage has the deepest intrusion into the blade.

2. The damaged blade will introduce a local modification of the slip effects at the outlet, and this will influence the discharge through the blade channels on both sides of the damaged blades. This will result in a local increase of the discharge that can be measured as a pulse of pressure drop in the vaneless space sensors every time the damaged blade passes through the sensors with a frequency equal to the rotational frequency of the runner. The local increase of the discharge will result in a local reduction of the pressure in the stationary guide vane channels due to Bernoulli principle and conservation of energy (hydraulic energy is not transformed into mechanical work in the stationary parts of the turbine). On Figures 7 and 8 given are diagrams with instantaneous discharge through the guide vane and runner channels for a randomly selected time step in the simulation. An increase of about 9% from the mean from all runner channels can be seen for channel number 1, which is bounded by the pressure side of the damaged blade. The discharge through the runner channels is also affected by the RSI pressure field and an ND2 pattern can also be seen on Figure 8. In the guide vanes, the maximum discharge follows the leading-edge position of the runner, which is number 13 for the observed time step on Figure 7.

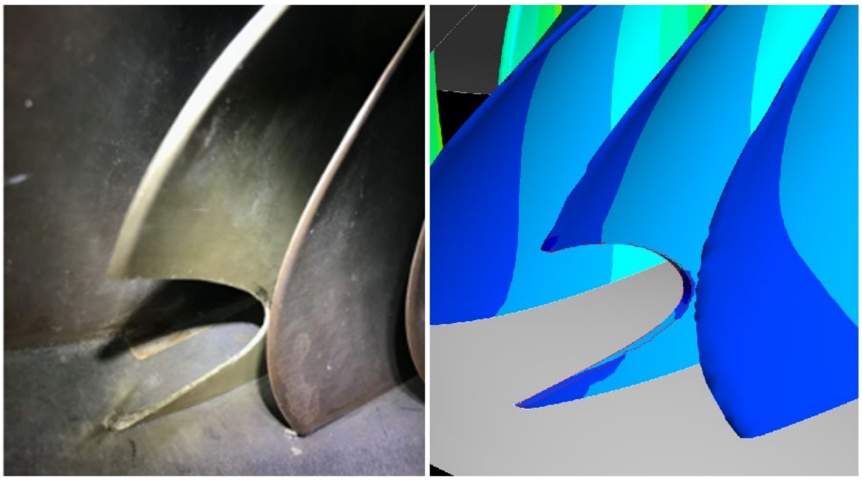

Figure 4. A side-by-side view of the blade damage in Case-8 of the experiment (left), and the numerically reproduced blade damage (right) from approximately the same viewing angle. The blades in the numerical view are colored by the pressure contours.

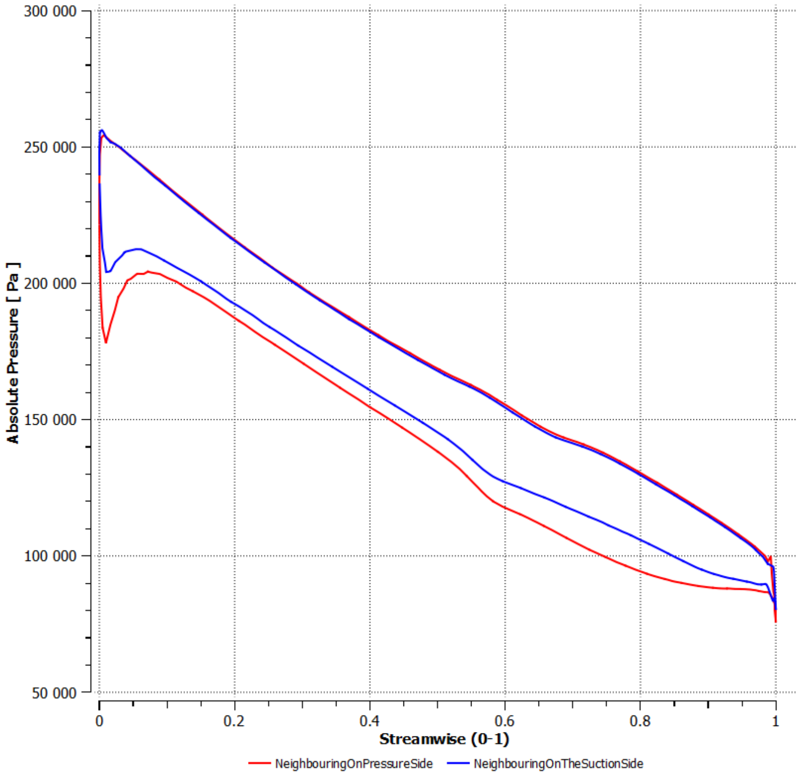

Figure 5. Streamwise distribution of the absolute pressure along the pressure and suctions side of both adjacent blades next to the damaged blade. The streamwise length is normalized.

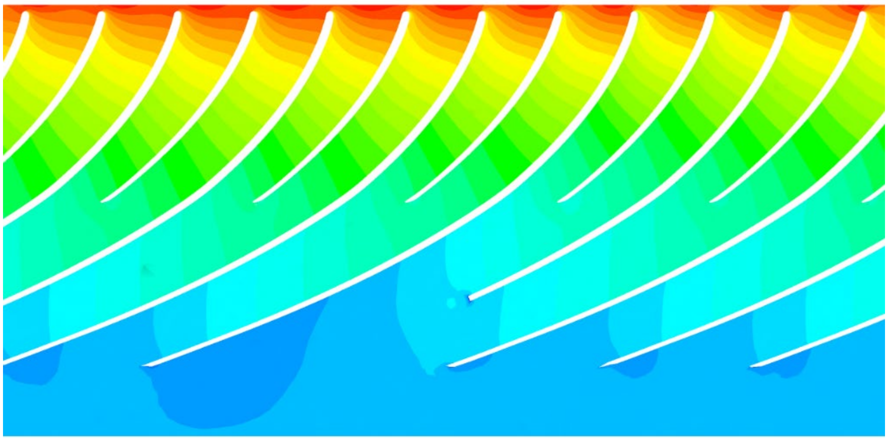

Figure 6. Pressure contours in the plane of the blades showing the distortion of the pressure field around the damaged area. The spanwise location is where the blade damage has the deepest intrusion into the blade itself.

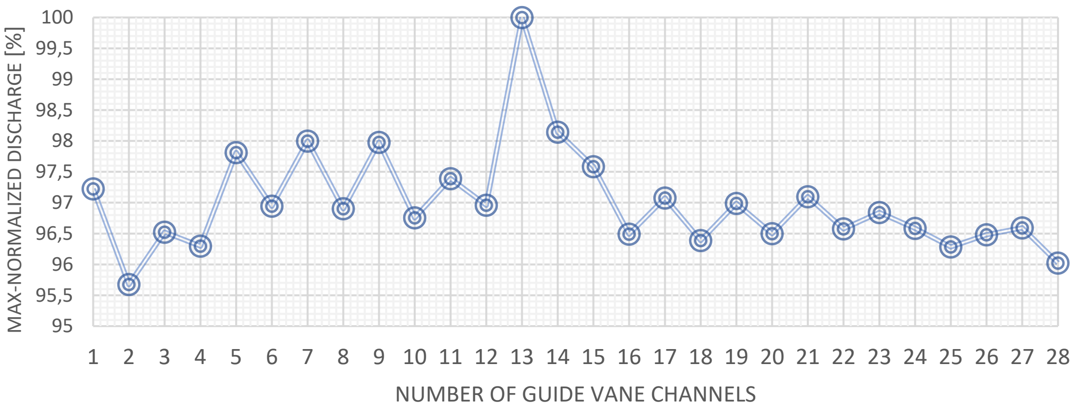

Figure 7. Instantaneous discharge in all guide vane channels, normalized by the maximum discharge found in channel number 13 for the given time step in the simulation. The leading edge of the damaged blade is closely positioned behind the channel 13 in this time step.

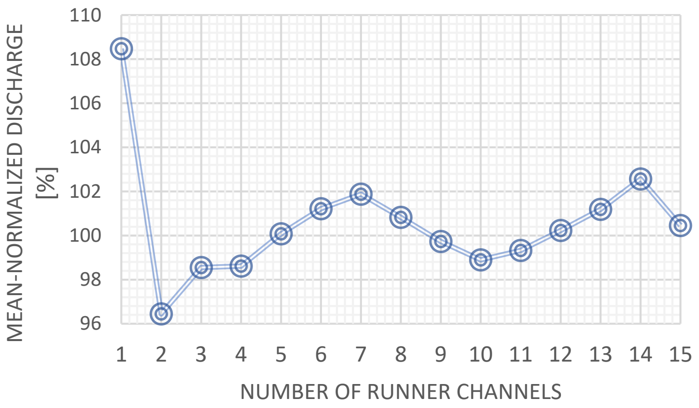

Figure 8. Instantaneous discharge in all runner channels formed by the main blades, normalized by the mean discharge for the given time step in the simulation. The channel that is bounded by the pressure side of the damaged blade is marked with number 1, and the discharge remains the highest amongst all channels for all time steps in the simulation.

Relevance/utilization

This study has practical implications, offering insights into turbine performance under adverse conditions. It can lead to improved methods for monitoring and early detection of structural issues in turbines, enhancing their reliability. The damage of a turbine blade only has local effects on the flow field, and this is typically not enough to affect the main performance characteristics, such as efficiency, vibrations, noise, etc. Due to this, the inspection intervals must be short enough to detect the damage in its early phase and prevent a more costly one, but this is not always possible or practical. Therefore, understanding the hydrodynamic behavior of a turbine with a damaged blade is important for developing effective and simple methods for detection and prevention. The knowledge from the short study briefly presented here may help to design systems to considerably reduce the downtime and unexpected unit shut down and improve the plant's overall reliability.

Conclusion

The performed simulation of a single operating point of the Francis turbine has revealed important insights into the behavior of a turbine with blade damage resembling a "shark-bite" fatigue failure. Key findings include the local effects of redistribution of the blade loading, where the missing part of the blade is, changes in pressure and vibration signatures, and the presence of characteristic frequencies. While the study successfully identified the detached fragment during turbine operation, no definitive changes were observed during crack growth, possibly due to the nature of the crack aperture created by the cutting tool. Nonetheless, these results hold significance for the continued operation of hydropower plants, offering valuable data for potential early detection of structural issues in Francis turbines. Further research in this area may enhance our ability to monitor and manage turbine health, contributing to the long-term reliability and performance of hydropower systems.

References and links to publications and thesis

[1] G K Støren *et al* 2020 *J. Phys.: Conf. Ser.* **1608** 012003 https://iopscience.iop.org/article/10.1088/1742-6596/1608/1/012003

[2] G K Støren 2020 Signature investigation of typical faults on a Francis turbine," Master Thesis, NTNU https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2779679