IGHEM 2012
The 9th International conference on hydraulic efficiency measurements
Trondheim, Norway
June 27th - 30th, 2012

Strain gauge measurements of rotating parts with telemetry

Johannes Löfflad, Marco Eissner, Bernd Graf

Voith Hydro Holding GmbH & Co. KG
Alexanderstr. 11, 89522 Heidenheim, GERMANY

1. Abstract

Modern design of hydraulic turbines aims to achieve very high levels of efficiency and structural integrity in the environment of highly variable loading conditions. To combine those requirements, a profound knowledge of static and dynamic loads acting on hydraulic components is necessary.

Dynamic loadings of hydro runners strongly depend on head range and required operating conditions. The knowledge of dynamic loads and stresses is often derived from strain gauge measurements.

This contribution describes the equipment and procedure of strain gauge measurements at hydro turbines, including the challenges to overcome during such tests. It provides an overview of strain gauge test results for stationary as well as for transient load conditions and the arrangement of strain gauge measurement for all typical hydro turbines are shown with their respective challenges.

The measurement solutions and results for Francis, Kaplan and Pelton machines are discussed in the following paper. The main focus is given to protection of measuring lines, online transmission of data, evaluation of transient operating conditions and life-time forecast by analyzing the measured data.

Keywords:

Strain gauge test, static and dynamic loading, stationary and transient load condition

2. Introduction

Getting a deeper understanding of the dynamic behaviour of water turbines becomes essential with the last years. More and more it comes alight, that mainly the dynamics are driving the partial damage of turbine components like runners and generators.
With the recommendation to reduce weight of components and increase efficiency of turbines, the dynamic sensitive of these machines changed completely.
Within the last years the technical progresses comes up to a point, where it is possible to measure signals at rotating parts and get them online into the stationary system via telemetry.
This technology is very powerful to improve the understanding of the dynamic behaviour of water turbines, because it is also possible to measure these signals time synchronous with signals from the stationary system, like pressure pulsations or vibration values.

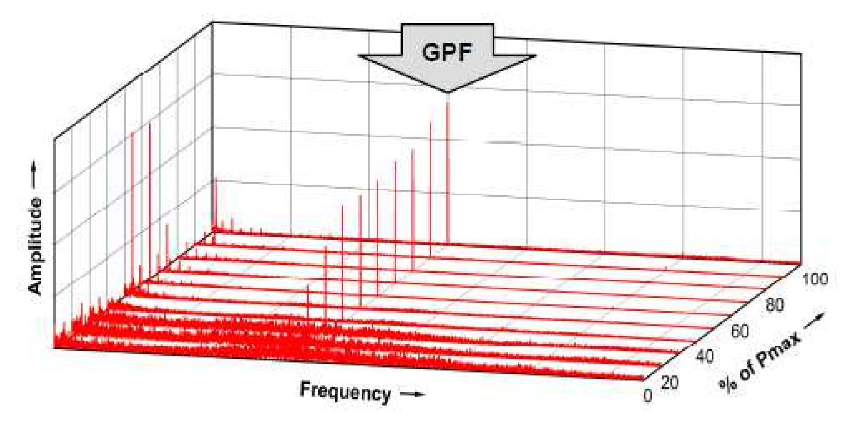


Figure 1: Typical frequency spectra of measured strains for a high head Francis runner

At low outputs, a stochastic behaviour with broad band frequency content is present. At part load condition, the typical low frequency excitation caused by vortex rope phenomena (related to Rheingans frequency) appears in the frequency spectra. From part load to full load, a higher frequency component arising from RSI, the so called "Gate Passing Frequency" (GPF), dominates the frequency spectra of higher head Francis runners.

3. Method

3.1.Functionality

For measuring the stresses on a Francis runner, a telemetry system is used. This kind of system provides a contact less transmission of sensor signals (generally strain gauges) from the rotating system to a stationary receiver. Hence the system consists of a rotating unit (emitter) and a stationary unit (receiver).
The sensor signals are amplified and are converted in a first modulation (voltage → frequency) to a subcarrier frequency. In a mixer the channel specific subcarrier frequencies are merged. The subcarrier mix is modulated to the main carrier frequency by HF-modulator. This signal abuts at the sending antenna and can be received by stationary antennas.
The demodulator in the receiver converts the HF-signal back to a subcarrier mix and in a second step back to a voltage signal (frequency → voltage). An analog amplifier provides the analog signals (± 10 V or 4-20mA) to the output of the receiver.

3.2.Capabilities

Following table gives an overview of the capabilities of the telemetry system used in hydro power plants.

Component	Unit-Type	Measurement-Type	Sensor location	Data Transmission	
				Air	Water
Turbine	Francis / Pump / Pumpturbine	Runner strain	Trailing edge Leading edge	✓	✓
Turbine	Francis / Pump / Pumpturbine	Static pressure	Runner cone	✓	✓
Turbine	Francis / Pump / Pumpturbine	Axial shaft torque	Shaft	✓	
Turbine	Kaplan	Runner strain	Trailing edge Leading edge Fillet, Groove	✓	✓
Turbine	Kaplan	Axial thrust / Shaft torque	Turbine shaft	✓	
Turbine	Pelton	Runner Strain	Root	✓	
Generator	Synchron	Rotor/pole strain	Pole fixation	✓	
Generator	Synchron / asynchron	Axial and bending Shaft torque; shear forces	Generator shaft	✓	

Table 1: Overview of applications in hydro power plants

3.3.Configurations

Typically two different applications of the system installation are practicable. For Units having a central air admission pipe, going from the runner to the top of the generator, the data transfer is realized in air. For this application, the rotating antenna is located at the top of the generator, where also the power supply for the data acquisition system is fitted. To minimize the data transfer length, the stationary antenna is located as close as possible to the rotating one.

For Units without central air admission pipe, the data transfer is warranted by sending through water. For this application, the stationary antenna is located below the rotating runner at the draft tube. To achieve a stable data transfer, the rotating antenna is installed on runner band side, in between two runner blades.

In order to maximize the system availability for both types of applications, an intermediary remote system is used to switch on/off the telemetry system at any time.

3.3.1. Sending through air

The data transmission through air is the standard configuration for strain gauge measurements. For this application the telemetry system is located at the runner cone in a waterproof construction, which is specially adapted for the test setup. The signal wires lead the strain signal from the strain gauge position along the runner blade trailing edge to the waterproof construction. The converted and modulated signal is lead by the antenna cable through the shaft to the top of the generator where also the power supply, the remote system and the rotating antenna is located.

In case of an extended test which exceeds the power supply capacity, the batteries can be changed easily. With the realized application it is not necessary to dewater the unit.

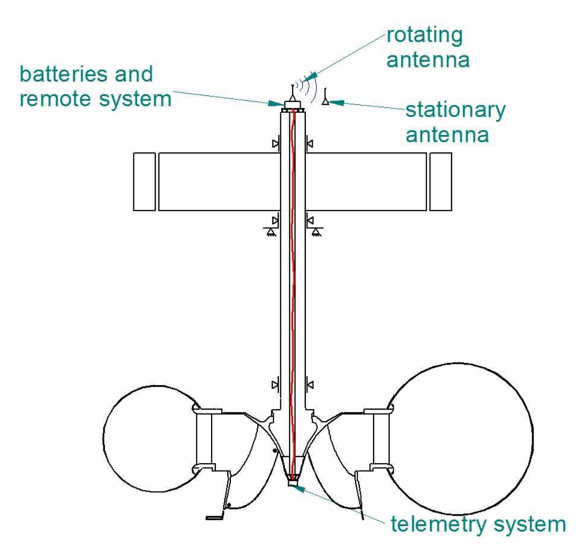


Figure 2: Application sending through air

3.3.2. Sending through water

Whereas at units without a central air admission pipe the data transmission in air is not possible. In that case the data transmission from the rotating to the stationary part is accomplished in water.
The method of strain gauge signal erection is the same for this configuration, but the location of the power supply, the remote system and the rotating and stationary antenna differs from the data transmission through air. All these parts are located in the waterproof construction at the runner cone, where also the telemetry system is fitted. Several stationary antennas are distributed at the draft tube, as close as possible to the rotating runner.

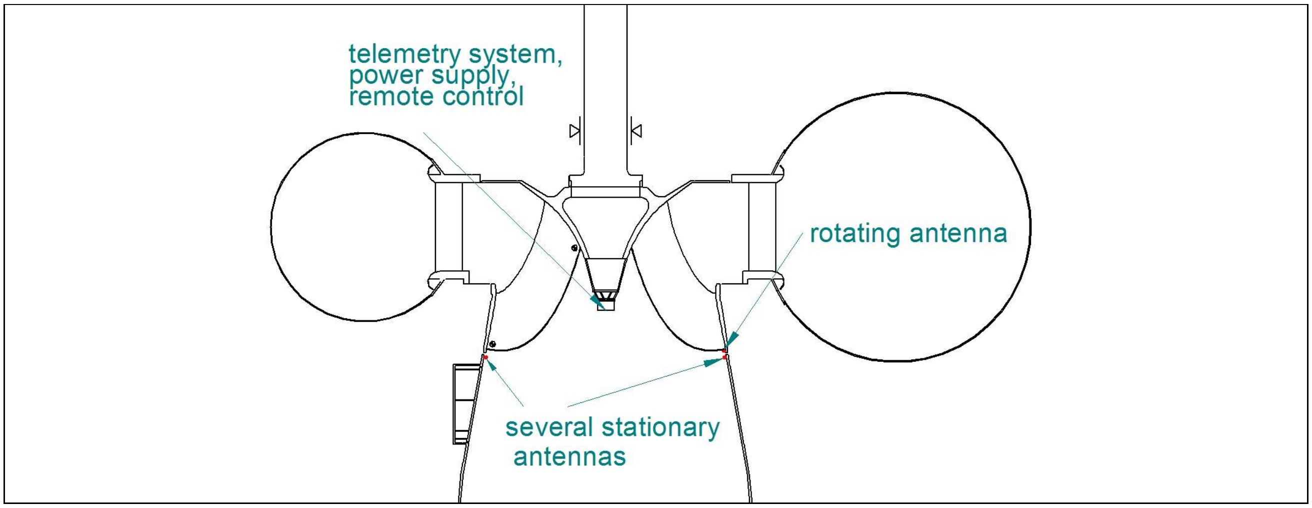


Figure 3: Application sending through water

3.4.Simulation in preprocessing

The strain gauge positions are derived from static Finite Element results. Based on the stress distribution for several calculated load cases the proposed strain gauge position and orientation are defined. Usually highest static and dynamic stresses on a Francis runner occur close to the trailing edge, at the transition to band and crown side.
See following figure with typical stress distribution and orientation of main stresses for a Francis runner at trailing edge to band (left side) and at trailing edge to crown (right side). Arrows indicate the orientation of the principal stress, the length of the arrows is magnitude based.

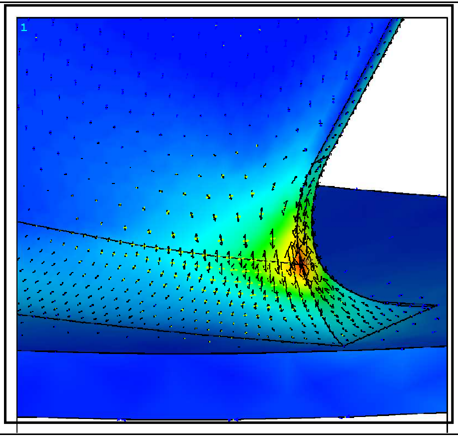
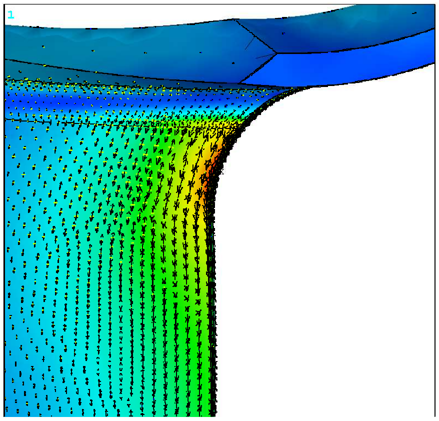
	
stress distribution at trailing edge to band	stress distribution at trailing edge to crown

Figure 4: stress distribution at a Francis runner trailing edge to band and to crown

Practically it is not possible to measure at the maximum peak stress. This limitation is caused by the size of the strain gauge and the necessary protection layer against irruption of water.

3.5.Application

This section introduces the definition of the strain gauge positions at the prototype, how to apply the strain gauges and how to protect them against water irruption.

3.5.1. Patterns

In order to get the exact position for the strain gauge application, special tools are used. For exact position of the strain gauge sensor, steel templates are used. These are derived from the CAD-model of the Francis runner.

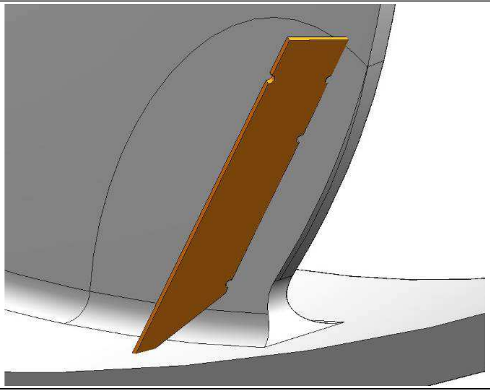
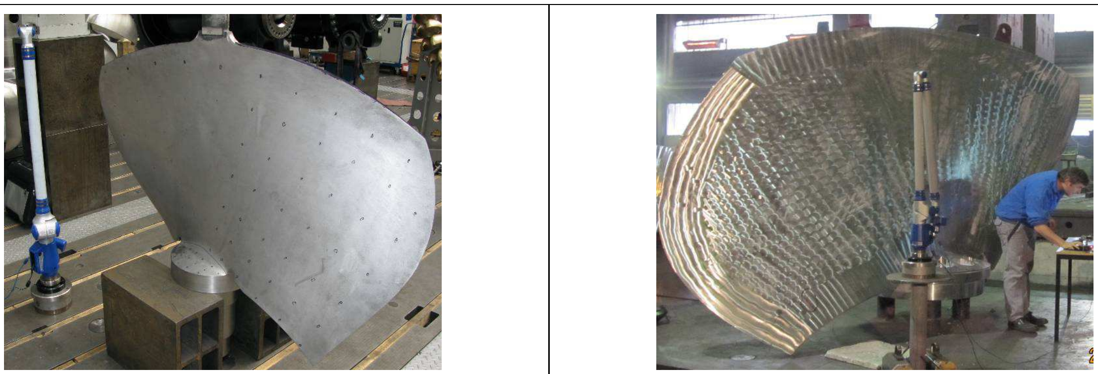
	
Templates designed in CAD-System	Templates used at site

Figure 5: Templates used for strain gauge application

3.5.2. FARO-Arm

Another possibility to locate exact strain gauge positions is the usage of the FARO-Arm. This method of defining strain gauge positions on the prototype is used specially for Kaplan runners, where the usage of steel templates is not practicable.



FARO-Arm used for model machines

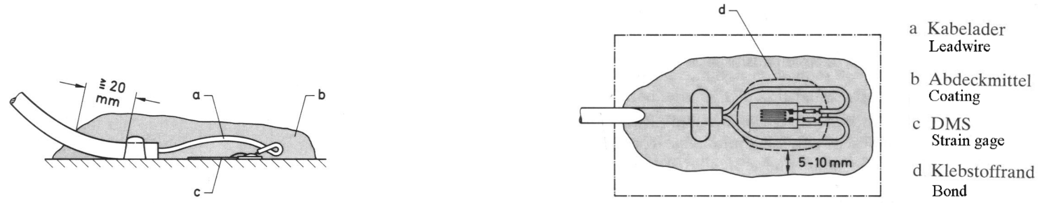
FARO-Arm used for prototype size

Figure 6: strain gauge positions with FARO-Arm

3.5.3. Strain gauge application

The strain gauges are bond to the surface by using a modified alkyl cyanoacrylate compound. This bond cures at room temperature and gives a very thin, uniform layer of adhesive for optimum bond performance.

A special coating procedure is required for strain gauges on water immersed surfaces. It is necessary not only to protect the strain gauge itself but also the soldering and the lead wire. A cross section of a typical water resistant strain gauge application is shown in Figure 7.



Beispiel für die Schutzabdeckung einer DMS-Meßstelle

Example for the protective coating of a strain gage installation

Unidirectional strain gauge

Local coating

Aluminum foil

Figure 7: Protective coating of strain gauge installation

3.5.4. Protection Layer

The cables going from the strain gauges to the data acquisition unit are fixed to the surface by a double-sided adhesive tape. In order to protect the strain gauge wires against water irruption, at least one protection layer is used. The first layer is a two-component epoxy resin with excellent characteristics working under water and under pressure. For applying this layer, the surface has to be treated specially in order to improve the adhesion of the epoxy. The epoxy is shaped to minimize the effects on the hydraulic, see below figure.

In case of measuring under high pressure ($p > 3$ bar) or under special circumstances (e.g. high sand content), a second protection layer is used. This layer is a local coating developed to resist higher pressure (water tightness) and better resistance against erosion. For this application several layers have to be applied, see below figure.

	
First protection layer (epoxy resin)	Second protection layer (epoxy resin + coating)

Figure 8: protection layers for strain gauge application

In case of measuring a Francis runner, the cables from the band side are applied along the trailing edge (pressure or suction side) to crown side, where the data acquisition unit is located.

3.6.Measurement

3.6.1. Synchronous data acquisition

With the used telemetry system and the associated online data transmission, it is possible to record all signals from the strain gauges time synchronous with other signals, like static pressure, pressure pulsations, bearing and shaft vibrations and control panel signals.

Especially for transient load conditions like start up, stop, load rejections and change over operation of pump turbines a synchronous data acquisition has the following advantages compared with a data logger:

- Functionality check of the rotating measurement equipment
- Continuous optimization of the measurement program by online assessment of the measured strains
- Optimization of transient load conditions without dewatering (e.g. start-stop, load rejection)

3.6.2. Estimation of Systematic measurement uncertainty

1) For the calculation of uncertainty of runner stresses the uncertainty of the young’s modulus E and the uncertainty of the measured strain ε has to be considered.
2) The uncertainty of the Young’s modulus is assumed to be $f_E=\pm3\%$
3) The uncertainty in the measured strain is based on:

- Shunt calibration => sensitivity k, R_{SG} (Strain gauge), R_p (Shunt)
- Zero instability effects due to temperature, isolation, cabling
- Misalignment of the strain gauge

3.1) Shunt Calibration

$$\varepsilon = \frac{1}{k}\cdot\left(\frac{R_P}{R_{SG}+R_P}-1\right)\cdot 10^6 \quad \text{µm/m}$$

Thus the abs. uncertainty (e) is

$$e_{\varepsilon_c} = \pm\sqrt{\left(\left(\frac{\partial\varepsilon}{\partial k}\right)\cdot e_k\right)^2+\left(\left(\frac{\partial\varepsilon}{\partial R_{SG}}\right)\cdot e_{RSG}\right)^2+\left(\left(\frac{\partial\varepsilon}{\partial R_P}\right)\cdot e_P\right)^2} \quad \text{µm/m}$$

With

$$\frac{\partial\varepsilon}{\partial k} = -\frac{1}{k^2}\cdot\left(\frac{R_P}{R_{SG}+R_P}-1\right)\cdot 10^6$$

$$\frac{\partial\varepsilon}{\partial R_{SG}} = -\left(\frac{R_P}{k(R_{SG}+R_P)^2}\right)\cdot 10^6$$

$$\frac{\partial\varepsilon}{\partial R_P} = \frac{\frac{1}{R_{SG}+R_P}-\frac{R_P}{(R_{SG}+R_P)^2}}{k}.10^6 = \frac{R_{SG}}{k(R_{SG}+R_p)^2}*10^6$$

Strain gauge factor	f_K=1% (k=2.06)
Resistance of strain gauge	f_{SG}=0.5% (R_{SG}=350 Ohm)
Resistance of Shunt	f_P=0.02% (e.g. 349650 Ohm)

With said values the relative uncertainty in the calibration becomes:
e_c=±5,4 µm/m

3.2) Zero Instabilities
During the short term test zero shifts will occur and have to be considered in the estimation of uncertainty. They are measured before and after the test, for zeroing of signals, their average will be considered. These depend on environmental factors and can be estimated as follows:
f_c=±5.0%

3.3) Misalignment
Assuming that misalignment φ of the strain gauge will not exceed 10 to 15 deg. from the max. Stress axis the reduced stress σ can be calculated as

$$\varepsilon = \frac{1}{2}\cdot\varepsilon_{\max}(1+2\cos 2\varphi) \text{ µm/m}$$

Thus the uncertainty in misalignment is assumed to
f_m=±3.0% to 6.7%

4) Relative uncertainty of Strains
Based on the assumptions made before, the relative uncertainty in the measured strains is:

$$f_\varepsilon = \sqrt{f_c^2+f_z^2+f_m^2} \quad \%$$

$$f_\varepsilon = \pm 5.9\,\%$$

5) Relative uncertainty of Stress

$$f_\varepsilon = \pm\sqrt{f_\varepsilon^2+f_E^2} \quad \% \quad \text{—>} \quad f_\varepsilon = \pm 6.7\,\%$$

3.7. Data Evaluation

3.7.1. Online Assessment for special transient load conditions

Performing a strain gauge measurement by using a telemetry system offers the possibility of online assessment of recorded strain gauge data. Especially for transient load conditions, a fast and reliable online assessment of these load conditions is possible. They could be optimized in matters of time, dynamic loading and partial damage.

Start up procedure

The correlation between process parameter and time synchronous measured strains on the runner provides one major benefit of using a telemetry system, especially when modifying the start up sequence in order to improve the dynamic behaviour.
Following figure gives an overview of several start up procedures and measured strains on a Francis runner.

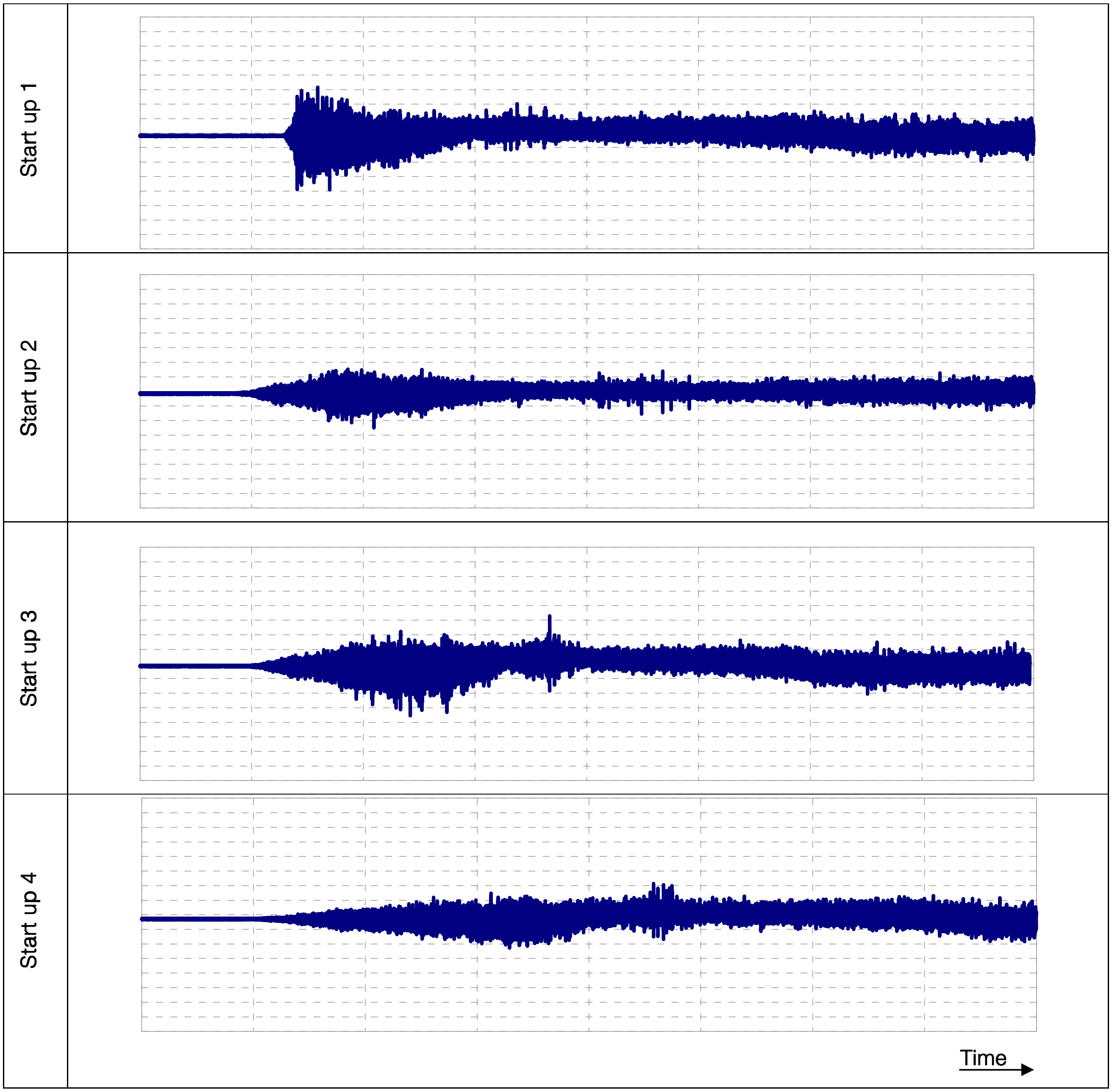


Figure 9: start up procedures and measured strains on a Francis runner for start up

The strain gauge signals in figure 9 are normalized to the mean stress at nominal speed. The level of mean stress after reaching nominal speed can not be influenced by the start up procedure, but as shown in figure 9 the dynamic part at the beginning is significantly reduced.

Load rejection

Besides the start up procedure also the behaviour during load rejection can be observed and, if necessary, be adapted. Following figure gives an overview of several stop sequences during load rejection and measured strains on a Francis runner.

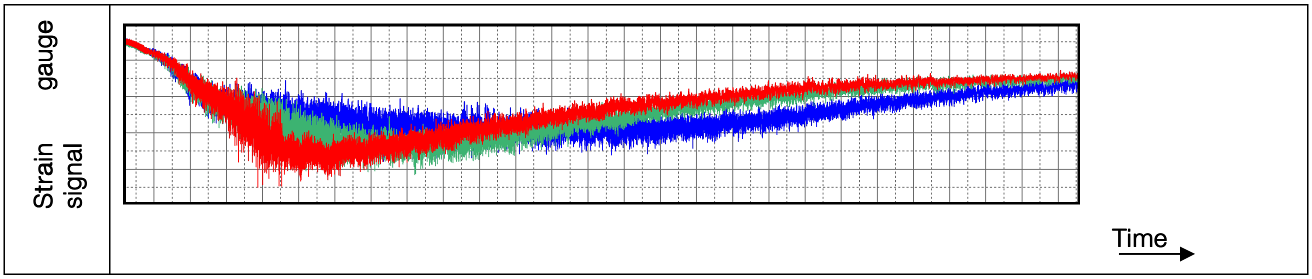


Figure 10: Stop sequence and measured strains on a Francis runner for load rejection

As visible in figure 10, the static as well the dynamic part of the strain gauge signal is very sensitive to different stop sequences.

Mean stress evaluation

Beside the evaluation of the transient load conditions also stationary load cases can be considered.
The figure below shows the trend of the mean normalized output.

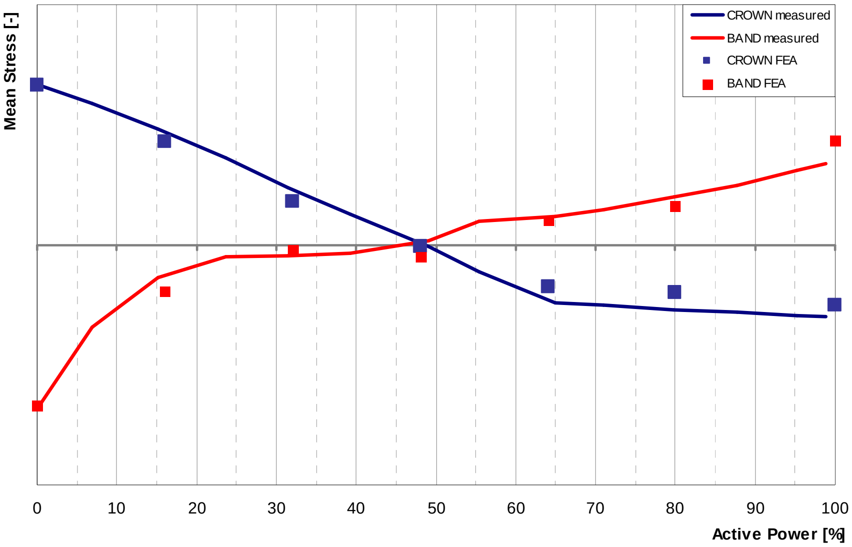


Figure 11: Normalized mean stress (measured and calculated) over output

The measured mean stresses are normalized to stresses at speed no load. The plotted lines indicate the characteristic for crown (blue) and band (red) from 0 to 100 percent output. The dots represent the calculated values from the Finite Element Analysis. It can be seen that the trend of stresses versus output is well represented. Deviations of measured and simulated stresses cannot be avoided and may have different reasons:

a) Geometrical deviations of real runner blade contour versus FEA model (manufacturing tolerances)
b) Deviations in loading conditions (real flow and head conditions versus CFD assumptions)
c) Deviation of real strain gauge position and assumed position in the FEA model (mismatch of location)
d) Flow disturbances due to strain gauge and wire application on runner blades (necessary protection during test)

The reasons (a) to (c) often result in an offset of measured stresses compared to the simulated ones. For the last reason (d), it can be observed that deviations at optimum and full load are sometimes higher compared to lower outputs. This might be caused by larger flow disturbances from strain gauge applications for well developed flow conditions. In order to improve the result quality as much as possible and to minimize the deviations, a careful preparation of the entire test including accompanying numerical simulations and a professional installation procedure is very important. Necessary actions must be coordinated between all parties. Once the mean stress comparison is done with reasonable accuracy, a closer look on dynamic stresses and strains is possible.

Dynamic stress evaluation

In addition to the evaluation of the mean stresses, also the dynamic parts of the signals are considered. For this a characteristic value is established. This value is called “characteristic peak-to-peak”, where approximately 3% of the highest peaks are neglected.

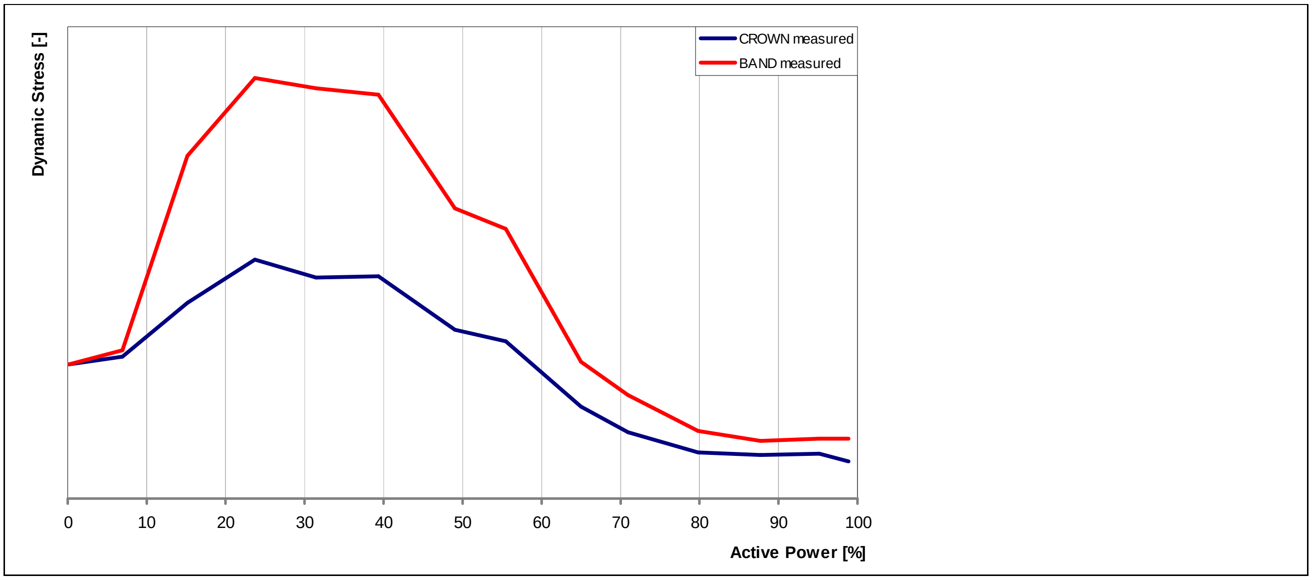


Figure 12: Normalized dynamic stress over output

The measured dynamic stresses (characteristic peak-to-peak) are normalized to speed no load values. As seen in above figure the dynamic value increases for stresses at crown (blue line) and band (red line) during part load. With higher loads the characteristic value is reduced significantly.

3.7.2. Partial Damage

Based on the measured strain signals on the runner and a load universe, a partial damage can be calculated in order to detect load cases, which should be avoided or the time running the unit in a special load case should be reduced in order to increase the life-time of the runner.
Following chart gives an overview of partial damage for several tested load conditions.

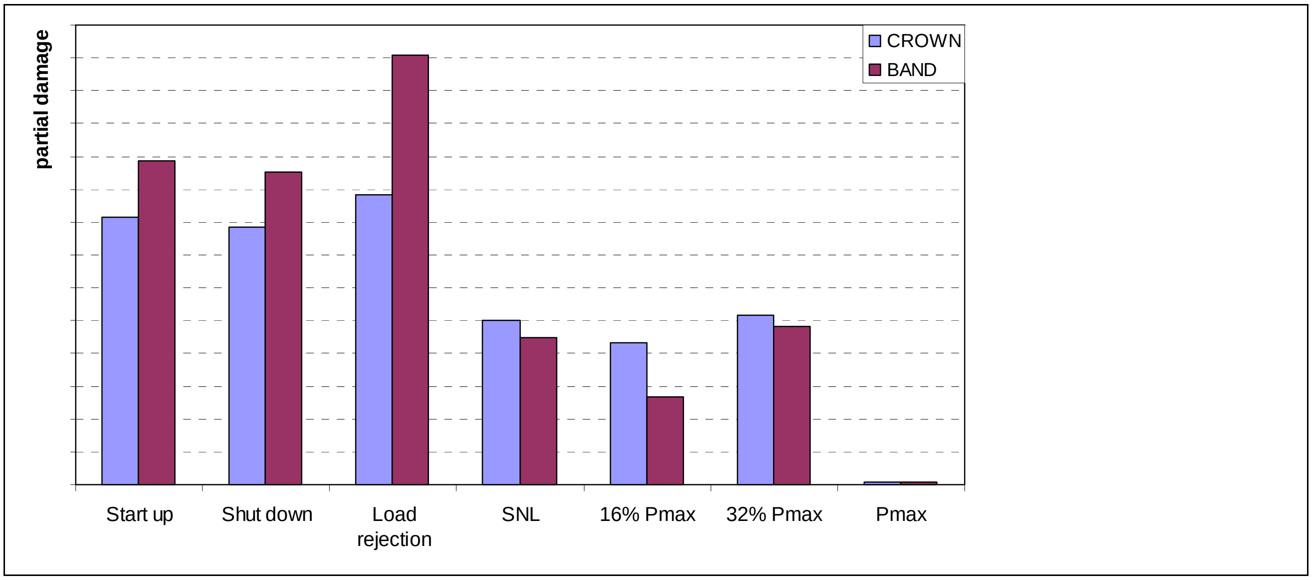


Figure 13: Normalized partial damage for different load cases

The partial damage is normalized to partial damage for P_{max}. The transient load conditions are the main fatigue contributor hence the improvement of these load cases increases the life-time of the runner most. For this example the partial damage at runner band is higher than at runner crown, depending on the runner this could also be changed.

4. Summary

Performing strain gauge measurements on rotating parts using telemetry systems is state of the art. Due to the possibility of data transmission through air and water, strain gauge measurements can be realized with almost no limitations of unit application and kind of runners.
Based on the database of strain gauge measurements, a calibrated procedure for predicting static and dynamic stresses has been developed and optimized. This procedure enables Voith Hydro to optimize runners with regard to static and dynamic stress as well as to fatigue behaviour.

5. References

Following table gives an overview of realized and projected strain gauge measurements at Voith Hydro using a telemetry system.

No. of realized and projected strain gauge measurements	**Francis runner**	**Kaplan runner**	**Pelton runner**
Data transmission through air	6	-	2
Data transmission through water	3	projected	n.a.