MEASUREMENTS OF THE REGULATING FORCES INSIDE OF A KAPLAN RUNNER VIA TELEMETRY

M. Eissner[1], M. Kondo[2]

[1]*Voith Digitial Solutions GmbH, marco.eissner@voith.com, Heidenheim, Germany*
[2]*Voith Hydro Holding GmbH & Co. KG, mauricio.kondo@voith.com, Heidenheim, Germany*

1 Abstract

Due to the increasing flexibility of the operating conditions and more stringent regulations of the power grid by the operators, the power unit experience much higher numbers of load cycles compared to stationary operation. By this increasing amount of primary frequency control operation the loadings on all components like the runner are strongly depending on the operation of these conditions and the quality of the turbine governor.
Whereas the lifetime for modes as power control or flow control, with a low number of cycles can be reached with a state of the art design with today´s technology, the lifetime for all dynamic amplitudes as primary frequency control cannot be directly derived from static model measurements or CFD analysis.

This has motivated a measurement campaign at a Kaplan runner mechanism using a self-developed procedure for the strain gauge application and data acquisition with a telemetry system.
Strain gauges were applied to measure the axial forces on the link as well as torque and bending stresses on the trunnions. Finally these signals were correlated with several signals in the stationary system.

This contribution describes the approach how the measurement inside a Kaplan runner was executed. It describes the measurement positions, some evaluations based on these measurements and shows the load changes between stationary operation and frequency control. There are also some figures presenting transient conditions like Start, Stop, Load Rejection and Load Ramps.

2 Introduction

This contribution describes how the measurement campaign was executed. It starts with the description of the setup, the measuring positions and evaluations done in the post-processing. It shall give a feeling how complex the installation sequence was with all organizational challenges and design challenges to fit the time schedule. The installation works and measurement itself was done over a period of 8 months. All sensors in the rotating system needed to survive the dry and wet commissioning with all special load cases. Special attention to the application needs to be given because the runner hub was filled with water.

3 Method

3.1 Functionality and measuring setup

All data from the rotating system was transmitted via a telemetry system which was mounted on the turbine shaft. Sensor cabling was lead from the runner hub through a hole to the turbine shaft and with a hole through the turbine shaft to the turbine pit area. Half- and full bridges were applied inside of the runner hub for measurement of the axial force on the links, the bending on the trunnions and the torque on the trunnions. Additionally a PT100 temperature sensor was installed in the runner hub to monitor water temperature. This signal was transmitted via the telemetry system, too.

The installation and measuring campaign was done in three steps:

I. Installation of the sensors at the dis-assembled runner in the erection bay and preparation of cables for turbine shaft installation to the runner (November 2015).
II. Turbine shaft installation to the runner and feed through of all cables through the shaft (February 2016).
III. Installation of the telemetry system and auxiliary sensors just before the measuring campaign (July 2016).

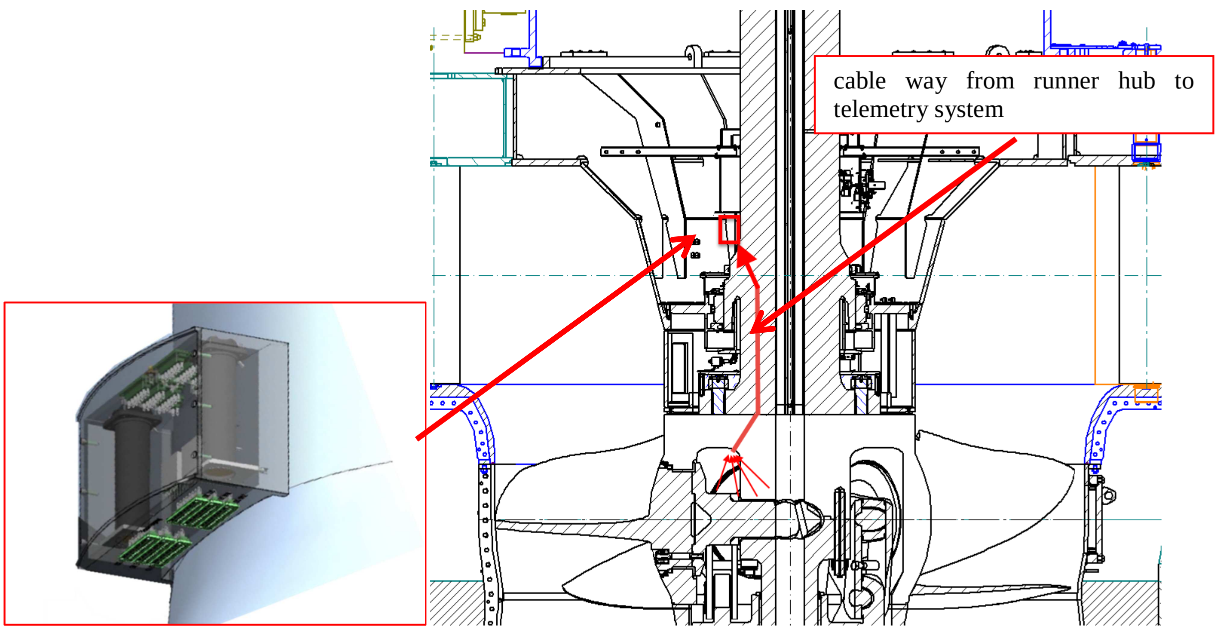


Figure 1: Telemetry setup

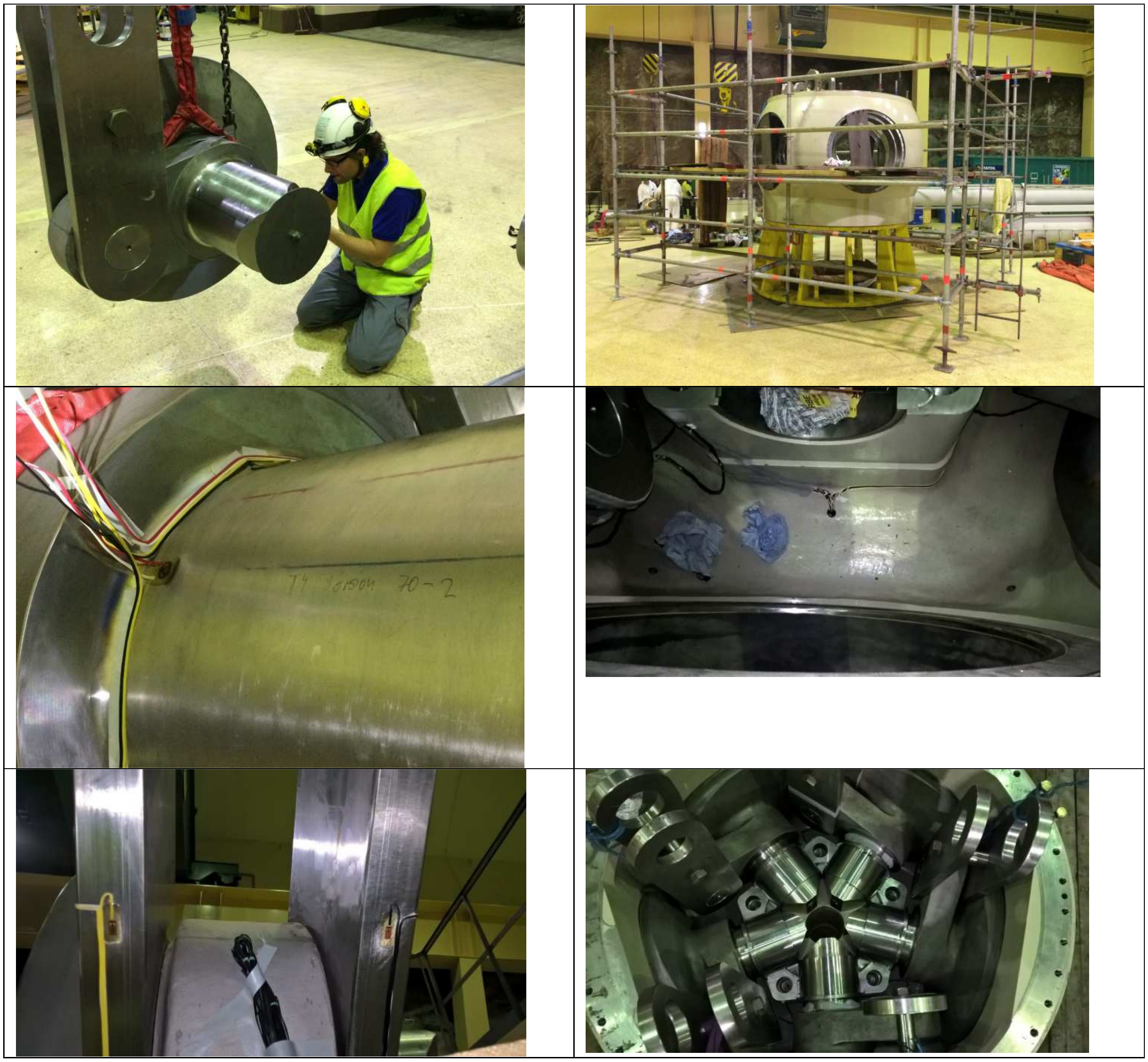


Figure 2: Impressions from application works

3.2 Measurements

3.2.1 Test program

Additionally to the standard program during stain gauge testing like stationary load points, start/stop and load rejections several frequency control tests, step sequences, Off cam steps and periodic load points have been tested.

	Description
Stationary	In steps from SNL to maximum power
Transient	Load ramp minimum-maximum-minimum
Transient	Start
Transient	Stop
Transient	Load rejection
Frequency control	Gain 20%/Hz
Frequency control	Gain 50%/Hz
Transient	Step sequence up-down-up 0,2%
Transient	Step sequence up-down-up 0,5%
Transient	Step sequence up-down-up 1%
Transient	Step sequence up-down-up 2%
Periodic	Sine wave ampl. 1%, T=150
Periodic	Sine wave ampl. 1%, T=100

Periodic	Sine wave ampl. 1%, T=60
Periodic	Sine wave ampl. 1%, T=40
Periodic	Sine wave ampl. 1%, T=25
Periodic	Sine wave ampl. 1%, T=15
Periodic	Sine wave ampl. 1%, T=10
Off cam	Fixed runner, guide vanes +-2%
Off cam	Fixed runner, guide vanes +-5%
Off cam	Fixed guide vanes, runner +-0,2°
Off cam	Fixed guide vanes, runner +-1°

Table 1: Overview of test program

3.2.2 Axial force on a link

The measurement of the axial force on the link was applied with a half-bridge once on the inner link and once on the outer link. Advantage of half-bridge application is that bending strains occurring at measurement location is cancelled and the signal itself is free of bending strain. Strain gauges are arranged at R1 and R4 in the Wheatstone bridge. R2 and R3 were completion resistances.

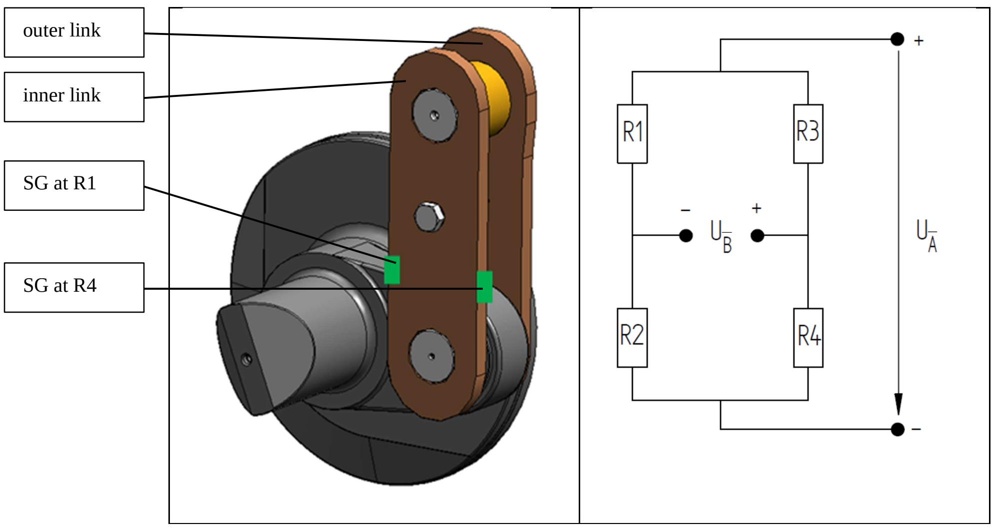


Figure 3: Sketch of strain gauge application on the links for tension

At the measuring cross section occurs an unequal stress/strain distribution. To get a more accurate axial force the measured signals were corrected with help of the FEA model. Correction factors were determined by a ratio of the analytical mean stress in the cross section and the local stress at SG position from the FEA model.

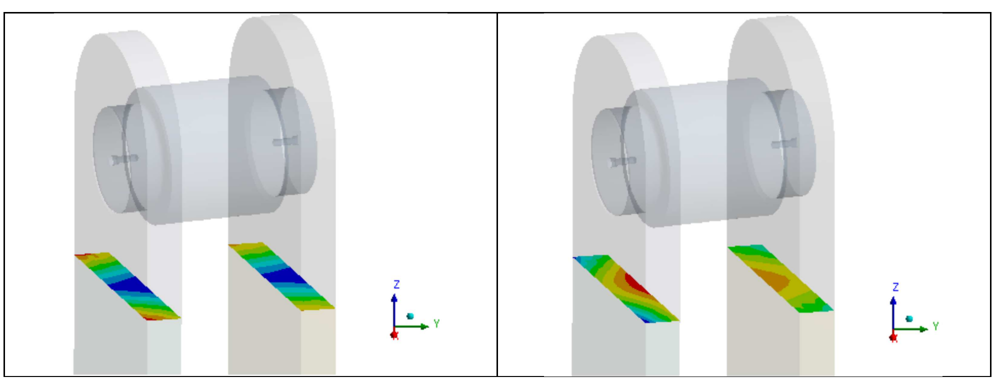


Figure 4: Unequal stress distribution in the SG cross section for tension and compression

3.2.3 Bending on a trunnion

The measurement of the bending on the trunnion was applied with a half-bridge. Axial forces on the trunnion were canceled. Additionally this setup was temperature compensated. Strain gauges are arranged at R1 and R2 in the Wheatstone bridge. R3 and R4 were completion resistances.

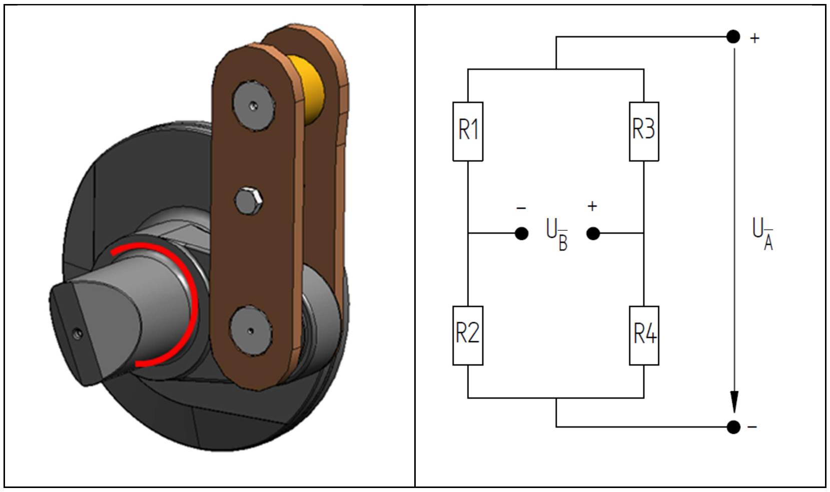


Figure 5: Sketch of strain gauge application on the trunnion for bending

3.2.4 *Torque on a trunnion*

The measurement of the torque on the trunnion was applied with a full-bridge. Axial force and bending on the trunnion were canceled. Additionally this setup was temperature compensated. Strain gauges are arranged at R1, R2, R3 and R4 in the Wheatstone bridge.

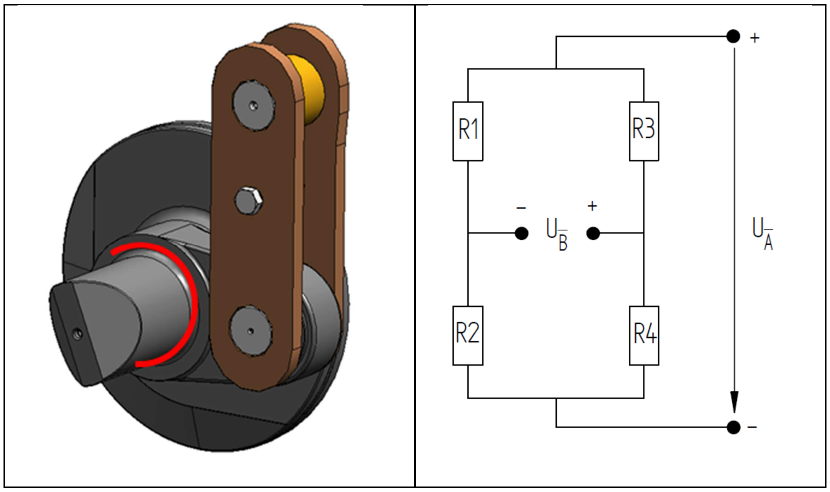


Figure 6: Sketch of strain gauge application on the trunnion for bending

3.2.5 *Auxiliary measurements*

In parallel and time synchronous the following signals have been recorded.

Designation	Description
p1’	Static pressure spiral case inlet
p2’	Static pressure draft tube end
p_{wk}	Winter-Kennedy differential pressure
P_OH_Open	Pressure Oil head Open
P_OH_Close	Pressure Oil head Close
P	Active Power
OPN_Dist	Opening guide vane
OPN_Runn	Opening runner blade
Speed	Rotational Speed
TRIGGER	Keyphasor on POLE 1
SP_RCV	Set point Runner control valve
SP_DCV	Set point guide vane control valve

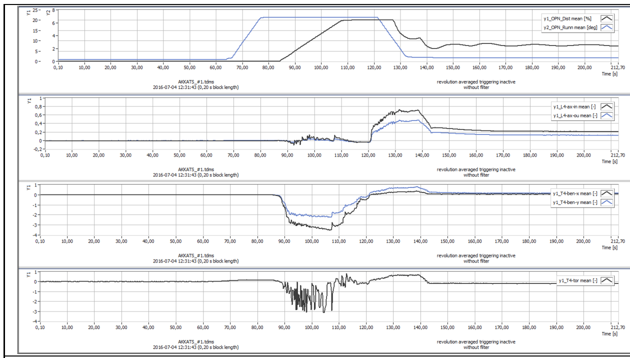
Table 2: Overview of auxiliary measurements

With the measurements of the spiral case inlet pressure, the draft tube end pressure and the relative discharge by means of Winter-Kennedy differential pressure for every load point a quite accurate net head could be calculated. That means the operating point of each measurement is known very well.
With the measurement of the oil head pressure for closing and opening the total force could be calculated and compared with the forces on the links.

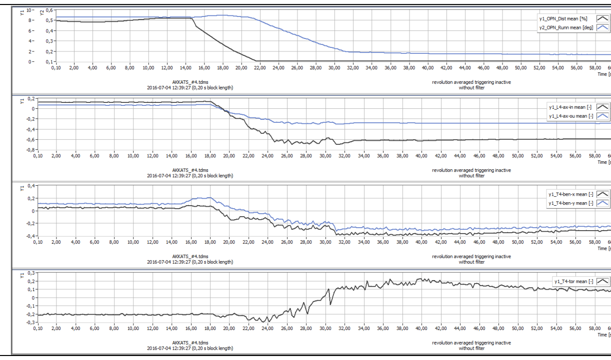
3.3 Data plots

The following pages shall give an overview of the resulting measuring data which was achieved during the measurement campaign. There are always the openings, followed by the link forces, the bending on the trunnion and the torque on the trunnion. The load cases shown are Start and Stop operation, load rejection from full load, frequency control and load ramp from SNL to full load.

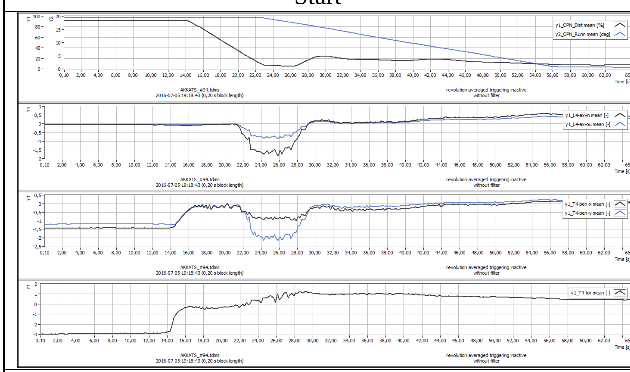
All this data is recorded time synchronous and give the possibility to correlate link forces achieved from the strain gauge test as well as from the pressure measurement at the servomotor.



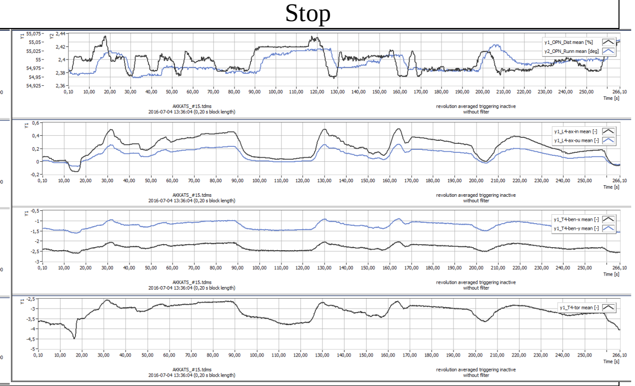
Start



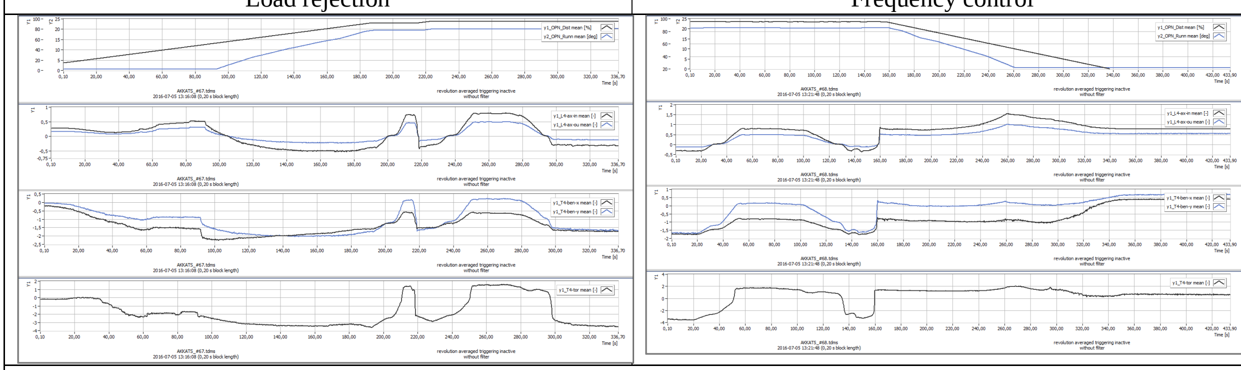
Stop



Load rejection



Frequency control



Load ramp

3.4 Correlation data

The design process of Kaplan runner uses a baseline theoretical mechanical model loaded by a hydraulic pressure field and centrifugal forces. The modern CFD analysis is calibrated with data from the model tests in order to produce a hydraulic representative condition and, consequently, representative pressure fields. However, the influences of homology deviations between model and prototype cannot be easily quantified without prototype measurements. The most decisive hydraulic loads applied in the mechanical sizing of the runner components are the axial thrust and the blade torques.

Since the friction involved in the system is very dominating, as long as the regulating forces are lower than the static friction of the system, the governor may vary the forces without moving the blades. Therefore, the analysis of mechanical loading must be performed for the cases of moving blades in a quasi-static test condition. The tested load ramps from minimum output up to maximum output and back to minimum deliver the load range in the Kaplan mechanism included in the complete continuous operating range at the available head.

Traditionally, the indirect measurement of the blade torque is done using the opening and closing forces calculated from the oil pressure at the governor lines in the vicinity of the oil head. This method became standard low-effort practice for checking the capacity of the blade servomotor. However, for the evaluation of the stress in the linkage mechanism with this approach, additional assumptions are inherent, such as the equally balanced loads among the blades. With the direct strain gauge measurements in the linkage, it is possible to validate the flow of forces between runner blade and blade servomotor. The calculation of the link forces out of the measured strain must consider the elasticity effects of the components, which result in different strain distributions under tension and compression over the cross-section of the link plates. Consequently, this results in a non-uniform stress distribution. For this case, the strain measurement in the links must be correlated to stress calculations made by FEA.

The link forces measured during ramping up and down provide two blade torque curves, which represent the required torque to open and close the blades. The difference between the opening and closing curves defines the friction torques. A good correlation between measured and computation data can be found. For this case, the hydraulic blade torques “Thyd(CFD)” from the resulting pressure fields computed by fluid dynamics are added to the centrifugal torque “Mdev” originated from the product of inertia of the blade geometry.

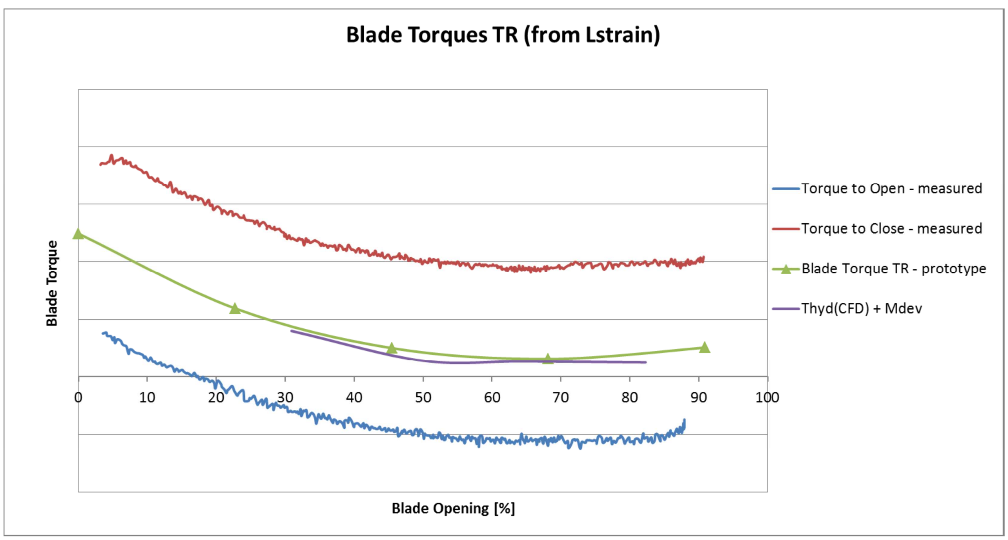


Figure 7: Validation of the blade torques from CFD, comparing to the indirectly measured values

3.5 Outlook to successful Kaplan runner design

The presented results of the Kaplan runner prototype measurements confirm the design and sizing procedure of the past by using the static loads and load conditions. For these static operating conditions the correlation of CFD data with model test measurements and the included prototype results match very well. The prediction of the static loads can be done accurately with today’s methods. In order to cover transient load conditions like start up, load changes or sudden emergency shut downs, design safety factors have been used. The safety factors have been derived from long term experience of the system suppliers in order to guarantee a long term and trouble free operation. Experienced based safety factors imply the risk that they might not be adequate when the design is changed for new requirements, as well as when the operating regime changes for modern requirements like frequent start stops or operation in primary frequency control where the blades are constantly moving with very small regulating cycles.

With these prototype measurements, the complete range of data including all transient conditions has been recorded. This will make it possible to define load cases and design criteria not only for the static operating condition, but for the transient condition and operation in primary frequency control with better accuracy than safety factors from the past.

Fast load changes are not the only focus, as increasing importance is being given to the primary frequency operation for Kaplan units as a mandatory requirement of the operators for grid stability. During the prototype measurements, different setups have been tested for primary frequency control response times and regulating functions. It is in the interest of the operator to provide as much flexibility and regulating ability as possible, but on the other hand, to also keep the wear and fatigue under control. The recorded data provides a good basis to evaluate the fatigue contribution of the different primary and secondary frequency control modes. This will allow for further optimization of the automation algorithms to balance the requirements of the grid and fast response in load changes compared to the fatigue contribution in the runner mechanism[2].

At the end, the goal is to define a standard load universe for Kaplan runners and the Kaplan regulation mechanism. This load universe should include all different load scenarios and operating conditions, as well as be adapted for the individual project depending upon the specific requirements. Sizing of the mechanism components, such as the links and the levers, will then be based upon a realistic fatigue approach rather than upon static stress results and safety factors. Loads will be correlated with the regulating forces, which include transient conditions and small movements in primary frequency control in addition to full opening and closing cycles. This will enhance the designs for the modern high efficiency requirements while not sacrificing robustness for long-term operation.

4 Conclusion

All applied sensors in the regulating mechanism could be measured over the complete test program. All signals from the rotating system could be correlated with signals in the stationary system as everything was recorded by a central data acquisition system. It was successfully demonstrated that with telemetry systems signals from the inside of a runner hub could be transmitted without losing data in such a complex prototype enviroment. In the preparation phase special attention needs to be given to the installation sequence and in most of the cases some design changes on the machine itself are necessary to make such complex measurement campaigns possible and successful. The organization of different project teams on contractor and client side is also a challenge which should not be underestimated as everything needs to fit in the project execution.

One of the mechanic design focuses for Kaplan runners is the wear and fatigue of the regulating mechanism. This is becoming more common due to the present operating requirements of the power suppliers, which increases the number of starts and stops, sudden load changes and primary frequency operation. Static conditions can be predicted well with state of the art CFD analysis and measured data from the model tests of the turbines; however, it is more challenging when looking into transient conditions. The results match well for the static operating conditions predicted by state of the art CFD simulations and data recorded in the laboratory during model turbine tests. For the transient conditions such as start-up, load change and operation in primary and secondary frequency control, the measured data will be analyzed and adjusted for load cases as input for future designs. Additionally, these operating conditions can be further optimized with an improved control automation to reduce the wear and fatigue of the mechanism. Ultimately, the obtained knowledge from the prototype measurements will improve the design and operating conditions of Kaplan runners.

5 Authors

Marco Eissner is measurement engineer at the Voith Digital Solutions in Heidenheim, Germany. He graduated from the University of Aalen, Germany, in mechanical engineering and joined Voith Hydro engineering center in the year 2007. Since then he worked in the department of prototype measurements at hydro turbines in the field of efficiency testing, strain gauge testing, vibration testing, sound measurements and experimental modal analysis. In 2016 the measurement department of Voith Hydro´s engineering center moved to the new Voith division Voith Digitial Solutions where he is also working as measurement engineer.

Mauricio Kondo was graduated in 2001 at the University of São Paulo (Brazil) as Bachelor of Sciences in Mechanical Engineering with emphasis in energy and fluid mechanics. In the same year he started at Voith Hydro Ltda. in São Paulo as turbine design engineer. Since joining Voith Hydro in Germany in 2002 he has been dealing with basic design of hydro turbines with special focus in double regulated Kaplan turbines.

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