Performance Upgrading of Hydraulic Machinery with the Help of CFD

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Summary In the developed countries the installation of new hydro electric power stations is nowadays very difficult and in many cases impossible. Here the upgrading of old power stations through replacement of critical components is the right measure to considerably increase the production of electricity by use of renewable resources. The development of such improved and more powerful components, most of all the turbine runner, is today possible based on numerical flow simulation and other modern CAE-tools. More than 50 % of old power plant installations have operational problems such as cavitation erosion, vibration of the structure due to vortices at off-design operation or severe noise. As an example the numerical engineering is described, that was carried out in order to upgrade a low head small hydro electric power station in Germany to increase power production by 30 % and to avoid cavitation erosion in the turbine runner. The new components have been installed and successfully put to operation. Now the turbine is performing well and is running surprisingly smooth.

1 Modernization of Old Hydro Electric Power Stations

Francis turbines are the standard type of hydraulic turbines used in the range of 50 to 500 m head. In total all over the world roughly 85 % of the hydraulic turbo machines are of the type Francis. The biggest hydroelectric Power plants such as Itaipu in the South of Brazil as well as Three Gorges Dam in China are equipped with Francis Turbines. But also for lower heads down to a few meters Francis turbines can be and already are successfully used.

Fig. 1 shows a Computer representation of a low head small hydro twin Francis turbine in southern Germany. Numerical analysis was made in order to find out what could be improved with the old machine that was built in the 1920s. In fact the two old runners were damaged seriously over the years

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of operation due to cavitation erosion, photograph in Fig. 2 shown below. Furthermore, the question was whether it was possible to increase the power output not only with improved efficiency but by increasing the discharge at full load in order to generate more electrical energy than before.

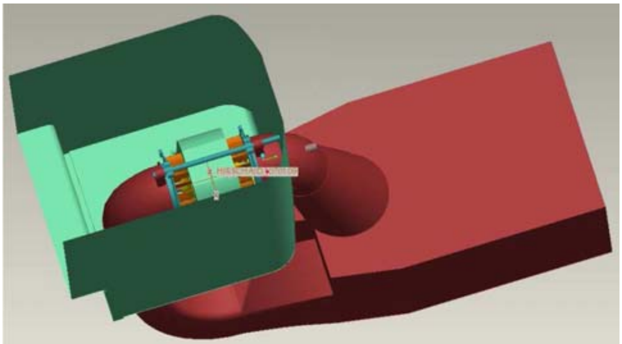

Fig. 1. Low head small hydro Francis turbine.

The task was quite ambitious because the machine had some special construction features, for instance, Fig. 1:

- no spiral casing,
- two runners on one shaft,
- two draft tubes converging into one outlet.

Therefore the question was not only, how to find a good solution to replace the existing runners in order to avoid cavitation erosion, but also to increase the output. First of all, it was to find out whether the other components of the machine were in good condition or not. As a consequence 3D flow simulation was carried out through the components of the existing machine, in fact through:

- the intake and the distributor,

Fig. 2. Cavitation erosion on the old runner.

- the runner,
- the bends and draft tubes.

In addition 2D analysis was performed to control the global data as well as the main dimensions of the turbine components. This was of special importance for the development of a replacement runner with less cavitation and increased energy production.

2 Analysis of Turbine Components

There were some doubts that the shape of the intake would lead to an acceptable quality of the flow in the distributor. It is clear, that if the flow distribution around the runner is far from being constant along the circumference, then rough running of the turbine would be the consequence. These doubts were justified due to the fact that the existing intake has a 90 degree step so that the incoming flow must separate from the edge, forming vortices in front of the machine, Fig. 3.

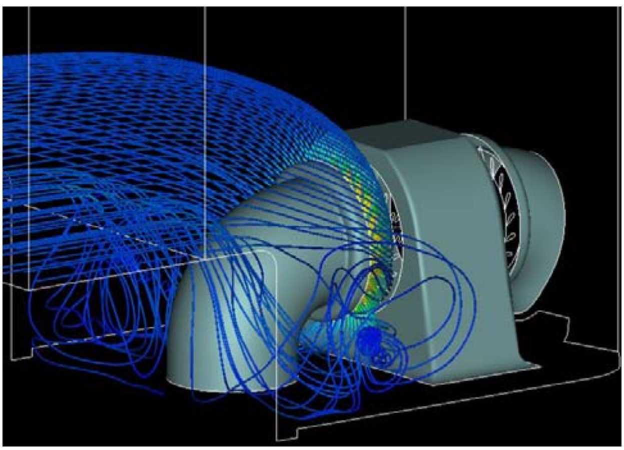

Fig. 3. Flow at turbine intake for best efficiency.

However, it was surprising how low the disturbance at the location of the turbine distributor in fact was. Fig. 4 shows the flow inside the guide vanes at mid span of the blades.

The flow velocities are indicated through colors, blue means very low flow, red means high flow velocities (here 8 m/s). The region in red forms nearly a circle, which means that the fluid entering the turbine runner is close to be perfectly distributed in terms of through flow as well as in terms of swirl. This gave confidence that a successful modernization of the existing power station

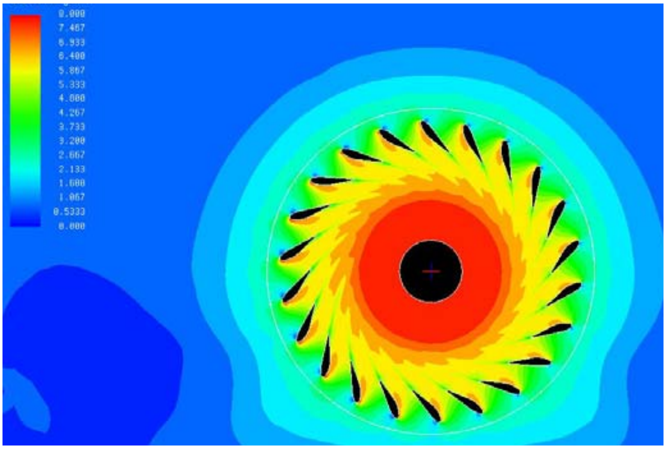

Fig. 4. Flow at the turbine intake and the wicket gate at mid span.

through replacement of important components with a new design was really possible.

It was known that the bends at both sides downstream of each runner could be a problem because there is no deceleration of the flow between runner outlet and the bend. However, with the help of some guiding profiles the turning of the flow inside the bend could be considerably improved leading to an acceptable flow pattern for the rest of both draft tubes.

3 Preliminary Design of a New Runner

Normally, when upgrading an existing old machine, the guide vanes as well as the runner are to be investigated and, in case it is necessary to replace these components to achieve the goals, a change in the construction has to be made. In order to get an idea how the new construction can look like, the Euler equation of turbo machinery can be used:

$$u_1\, c_{u1} - u_2\, c_{u2} = q\, H.$$

Using this equation it easily can be found that the existing contours lead to pretty strange blade shapes. Instead, by streamlining the flow channel and changing the radii of the leading edge as well as the trailing edge of the blading, much better blade shapes can be found, Fig. 5.

For the design point the following data were fixed: head $H = 10\, m$, discharge $Q = 10\ m^3/s$, runner speed $n = 214\ rpm$.

The runner speed had to be kept as before because the same generator should be used for the first time after modernization before the new one was ordered and installed. According to the above design condition the main dimensions were derived: $D_1 = 1{,}56\ m$, $D_2 = 1{,}65\ m$, $B_o = 0{,}52\ m$.

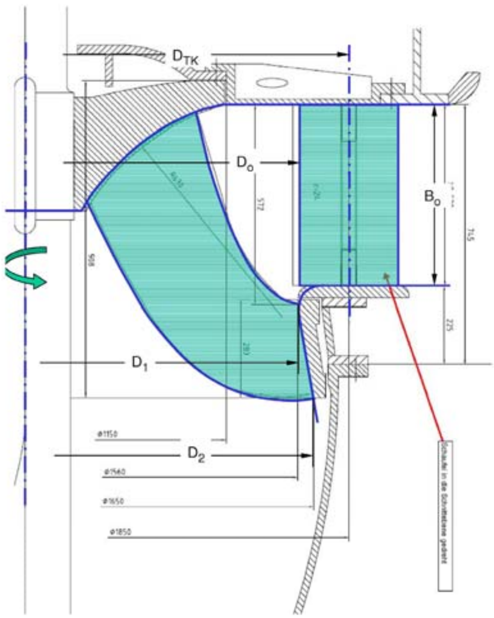

Fig. 5. Estimation of the new meridional contour by use of Euler's equation for turbo machinery.

Because the calculated angles are flow angles when using Euler's equation, the blade angles, that have to be used to define the final runner geometry, must be different to the first estimation. This difference between flow angles and blade angles must be found by using CFD.

4 Analysis of the Existing (Old) Runner

According to best engineering practice in the refurbishment and upgrading of old hydro electric power stations, the following steps have first been followed:

- assessment of the old runner geometry,
- based on this, creation of a numerical model for the old runner,
- flow simulation according to the old design condition,
- correlation of the results with observation, performance as well as cavitation erosion, if any.

The assessment of the old runner geometry was carried out using photogrammetry. The wetted surfaces were derived and based on this, the numerical model of the runner was created to perform the flow simulation. The result of the simulation shows clearly low pressure regions for the old runner at blade leading edge adjacent to the runner band, Fig. 6. As for many old runner designs in Francis turbines, leading edge cavitation is the consequence, when the pressure is below vapor pressure, which correlates well with the erosion of the material observed on the old dismantled runner.

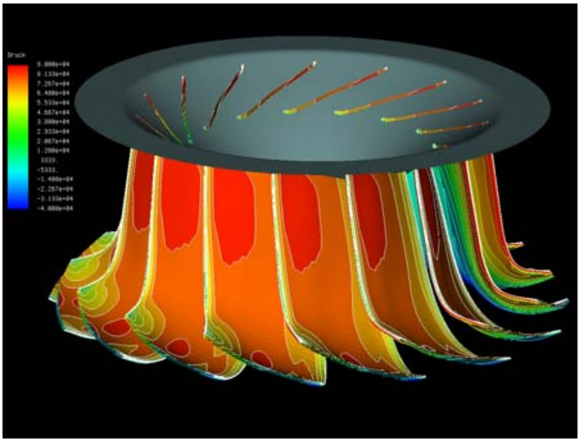

Fig. 6. Pressure distribution on the old runner blades at the inlet.

This is shown in Fig. 7. Cavitation at the runner inlet is likely to be the reason for the erosion that destroyed completely some parts of the blade leading edge, white circle.

This erosion is roughly the same at all blades of the old runner. The corresponding pressure distribution along the blade profile close to the band is given in Fig. 8. On the pressure side of the blade, the lowest pressure is at the leading edge.

Over some 20 % of the blade length there is no difference in pressure on both sides of the blade. Therefore, in this region the blade lift is zero, and the resulting torque is zero as well. This cannot lead to highest hydraulic

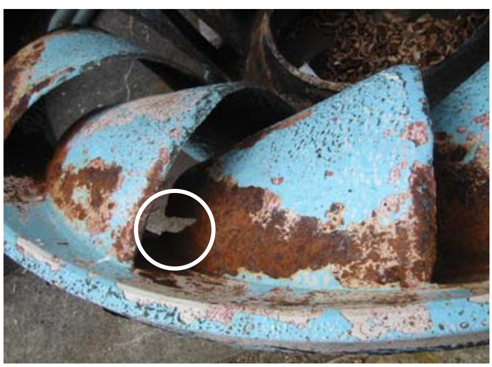

Fig. 7. Cavitation erosion at the blade's leading edge.

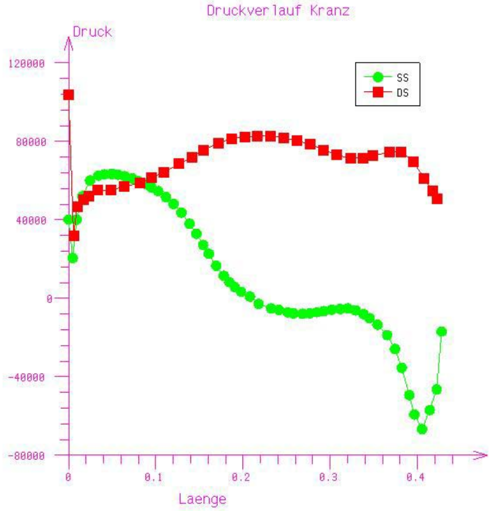

Fig. 8. Pressure on the blade close to the band, leading edge left. Ordinate: pressure, abscissa: chord length, SS: suction side, DS: pressure side.

efficiency. On the suction side of the runner the pressure distribution is shown in Fig. 9. This result correlates again quite well with the erosion as can be seen in Fig. 7. Note that the low pressure region is close to the trailing edge of the runner blades. In this region the cavitation starts to develop. The corresponding erosion of the material can only be downstream of this area, where the pressure rises up to values above vapor pressure.

In order to measure the improvement with the modernization, the performance of the old turbine was measured in the power station before the works were started.

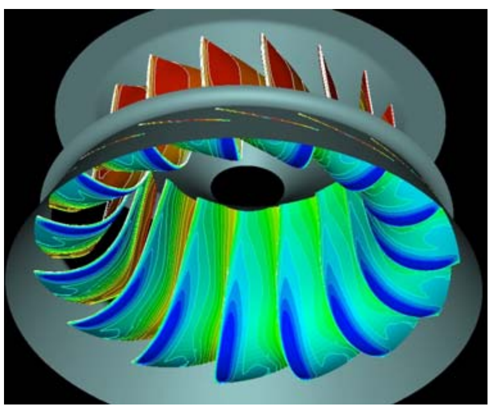

Fig. 9. Pressure on the suction side of the old runner.

Fig. 10 indicates the improvement which could be achieved with the modernization as well as the upgrading of the turbine. The graphic shows the turbine output depending on the discharge through the turbine. The discharge is regulated through different openings of the wicket gate. The data given for the power output are values produced at the outlet of the turbine generator. This means that all hydraulical, electrical as well as mechanical losses are included.

Prior to the upgrading of the turbine the maximum power output at full load was roughly 1200 kW. Now, after modernization, the power output is as much as 1600 kW. This is equivalent to an increase of nearly 30 % of the turbine power at full load operation. This shows clearly the potential for upgrading of old hydro electrical power stations, which are some 50 years old or more.

In addition, the operation of the turbine is remarkably smooth. It is well known that for Francis turbines smooth running can only be achieved in a certain range of operation around the point of best efficiency. Surprisingly, with the new design, the turbine is running smoothly from part load to full load.

5 Optimization of the New Runner

In modern hydraulic engineering for the development of a replacement runner, the approach is usually based on numerical flow simulation [1]. However, CFD is important, but only one part of the whole design process [2]. In total one has to:

- create the runner geometry (parametric design),

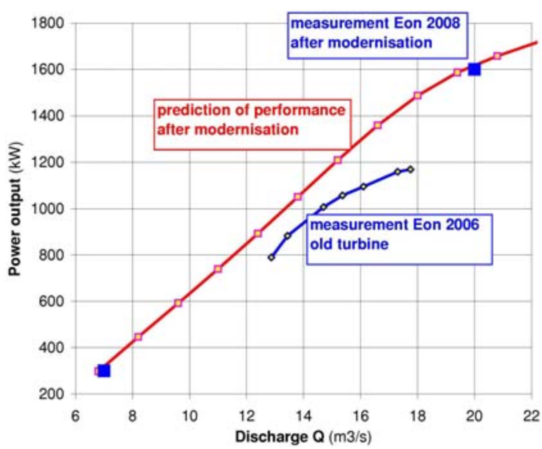

Fig. 10. Turbine performance before and after modernization.

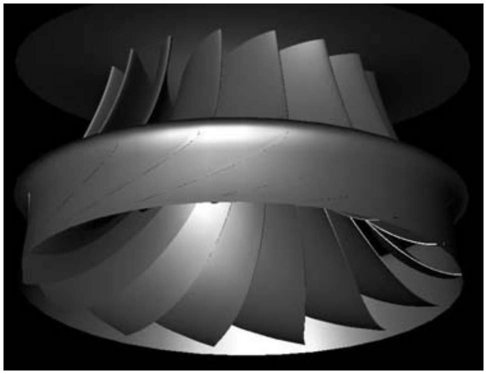

Fig. 11. Final runner design.

- generate the computational mesh automatically,
- specify (correct) boundary conditions,
- perform the flow simulation,
- visualize the important computation results in detail,
- summarize the main results to decide whether
- continue or stop.

Experience shows, that integration of all these parts is essential and one key for success [3]. Especially for low head turbines a good runner design is not easy to develop. A great number of steps has to be carried out not only to achieve the desired performance and hydraulic efficiency, but also to minimize cavitation inception at critical flow regimes [4]. In addition one has to minimize vibrations caused by rotor-stator interaction as well as those vibrations caused by draft tube vortex formation at off-design conditions.

The final runner geometry for the actual project is shown in Fig. 11. Typical for such a modern design is the curved shape of the blade trailing edges. This is in contrast to the old design philosophy, were the outlet edge of the runner blades was radial in any case.

What has been achieved in terms of pressure distribution on the runner blades can be seen in Fig. 12. Over a great portion of the profile length the blade loading is nearly constant. This is important in particular at the tip profiles near the band, because at the greater radii most of the runner torque is produced. Nevertheless, a small low pressure peak on the suction side at the blade's leading edge is still left, which is caused by the strong turning of the through flow at the runner inlet.

Comparison of Fig. 12 with Fig. 8 shows clearly the improvement against the old runner. The rear loading of the old blade is completely avoided.

Not to forget, that the operating conditions for the two figures are different. The pressure distribution in Fig. 8 corresponds to a considerable smaller

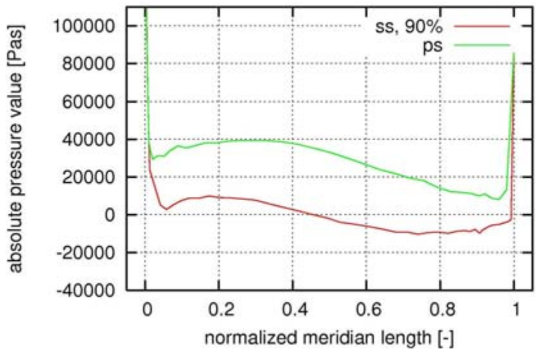

Fig. 12. Pressure distribution on the runner blade at the band, leading edge left.

discharge as for that distribution shown in Fig. 12. This indicates in addition a big step forward with the new runner design.

6 Parametric Runner Design

The new runner was optimized intuitively in a virtual reality environment [5]. Based on a set of parameters corresponding to the hydraulic data given by the power plant as well as to the geometrical data given by the existing turbine, the runner geometry is generated and the computational meshes are produced. Then the flow simulation is carried out according to the given operating condition for the turbine in an automated way. Within the same process the visualization is made so that the reaction of the flow on the change introduced to the runner geometry can be studied straight forward.

To give an impression of the shape of the new runner blades, the conformal mapping of three selected profiles is shown in Fig. 13 for the blade profiles at hub, mid span and at the band. Since this is a low head installation, the curvature of the blade profiles is low. However, the rotational speed as well as the meridional position of both the blade leading and trailing edge have an influence on the blade shape and in particular on the curvature of the blades.

In this sense it might be interesting to compare the preliminary dimensions and blade position shown in Fig. 5 with the final design after the complete numerical optimization. To do this the new runner is shown in Fig. 14 with the view from the inlet. The outlet cannot be shown in this representation.

It turns out that the shape of the preliminary blade leading edge fits quite well with the final runner design, [6]. This positive feedback is pretty important because in a typical project for rehabilitation or upgrading of an old power station one of the first questions is, whether or not a good solution is feasible.

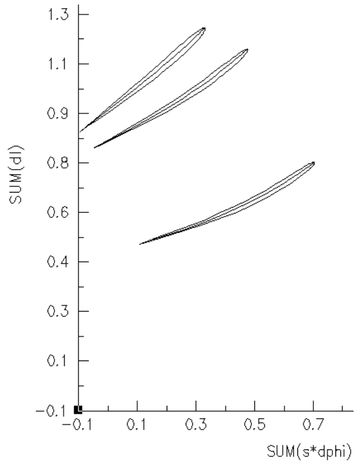

Fig. 13. Conformal mapping for the new blade profiles at the hub, mid span and band, from top to bottom.

7 Conclusion

After installation of the new components the first turbine is now in operation for a couple of months. The old generator is still in use with the consequence that, due to the limit of the existing generator, the maximum power is now limited to 1600 kW. The predicted potential of the old turbine could be realized, according to Fig. 11. As a result the performance of the turbine could be increased by more than 30 % due to the modernization measures. Also important is that the operation of the turbine is now remarkably smooth within the whole operating range from closed guide vanes to full open. This is quite unusual because the experience shows for Francis turbines for part load as well as for full load more or less rough running mostly because of vortices in the draft tube or some noise due to cavitation.

This example shows the great potential of increasing the production of electricity on the basis of renewable energy resources through upgrading of

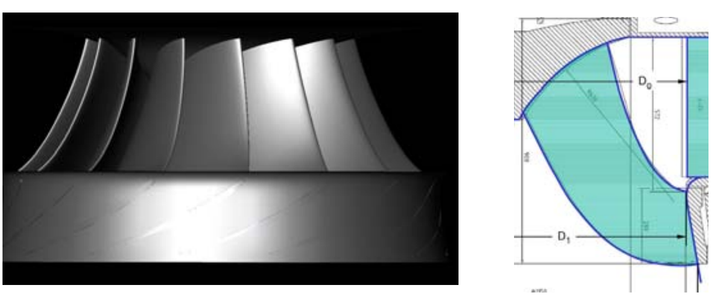

Fig. 14. Shape of runner blades at inlet, final versus preliminary design.

old hydro electric power stations. Especially in the developed countries the installation of new dams on rivers as well as reservoirs in the mountains is nowadays very difficult and in many cases impossible. In the old days the development of hydraulic turbines and pumps was made on the test stand, and only in few cases the design was going to be perfect. Nowadays with the upcoming numerical tools, it is possible to detect the weak parts of the existing designs. Combined with new materials now it is possible to put the old power station to their physical limit.

However, only the big companies have the equipment as well as the experienced personnel to perform a successful modernization. The engineering process is difficult, time consuming and therefore expensive. This is the reason why even in big companies upgrading engineering is only made for big hydro electric power stations, when the power output is above 20 MW up to the biggest turbines of 700 MW. For small and medium hydro power typically in the range from 500 kW up to 5 MW, the business is made by small and medium companies, and these companies are too small to develop tailor-made solutions in order to improve existing power stations.

Here universities play an important role because they develop and are using state of the art numerical tools for simulation as well as optimization. For the project described above, the hydraulic engineering was carried out at IHS, University of Stuttgart, the realization was made by Stellba Hydro, a small company in Baden-Württemberg, and the power plant operator is the great utility E.on. After the successful upgrading of turbine 1, these days the modernization of turbine 2 within the same power station is under installation.

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