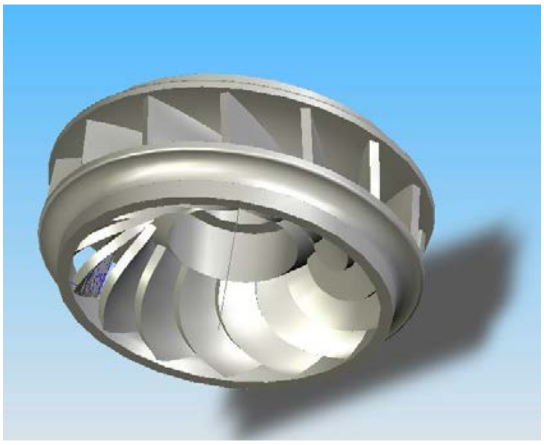
Hydraulic Design of Reaction Turbines



Including: Francis, Kaplan, Bulb turbines and Reversible Pump Turbines (RPT)

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Ingress

An Alab power plant is a complete data model for stationary and dynamic operation, loss analysis and calculation of power production. Turbines are necessary elements together with all other elements to make the power plant complete and interactive. Tools are included to create all actual elements matching your target.
This paper is focusing turbine design.
Alab´s turbine designer is creating a runner blade in a rather intuitive way. Namely that hydraulic energy should be converted to a moment as a smooth function of the meridional distance from inlet.
This is both mathematically and hydraulically a sound process and will contribute to a better understanding of hydraulics involved.

The Alab design process

Outline of method

Runner blade design is grounded on streamlines and the stream-surface method.
Blade thickness is calculated according to stress input.
A stream-tube is defined as the space between neighbouring streamlines and runner blades.
The blade is considered as a stream-surface or vortex sheet.
Blade thickness will increase velocities and influence streamline shape.
Euler equation for stream-tube i:

$$dM_i = \rho \cdot Q_{i\cdot} \cdot d(r \cdot c_u)_i$$

is just stating that a change in moment of momentum $r \cdot c_u$ will create a moment. Forces due to the moment will always be normal to the stream surface. Shear forces due to friction is not considered but will contribute to blade losses.

Introducing ω and integrating between runner inlet and – outlet the well-known equation for hydraulic efficiency will emerge.

$$\eta_h = \frac{(r \cdot c_u)_1 - (r \cdot c_u)_2}{g \cdot H_n}$$

η_h will not be the same for all stream-tubes, stream-tubes including ring- and hub contour will have lower efficiency, but to be able to continue on this path, a constant η_h have to be accepted.

Important:
Euler equation has no restrictions regarding how the moment of momentum is changed, but the path will be critical for flow distribution.

To use this possibility the relation $(\boldsymbol{r} \cdot \boldsymbol{c_u})_i = \boldsymbol{f}\left(\frac{\boldsymbol{m}}{\boldsymbol{m_i}}\right)$ is introduced.
m_i is the distance from inlet edge in the runner meridional section along the "centreline" of stream-tube i. $\boldsymbol{f}\left(\frac{\boldsymbol{m}}{\boldsymbol{m_i}}\right)$ defines runner blade geometry.
Using this information runner blade geometry with velocities, accelerations, flow angles and
blade angles necessary for running "Blade forge" will be available. "Blade forge" create a new stream surface and streamlines. Runner blade pressure differences are calculated and give input to methods calculating forces and moments.
The iteration process starts by estimating a set of streamlines based on complete constant axial section geometry. The target is the defined "Design point". The necessary freedom to keep the process running is the shape of the outlet edge in a horizontal view. This will be an output, depending mainly on outlet edge shape in the axial view.
The iteration process may fail to converge if the axial section geometry is improper.

A RPT runner blade will be designed as a turbine but with nominal data according to the actual case.

The Hydropower Workbench
Alab

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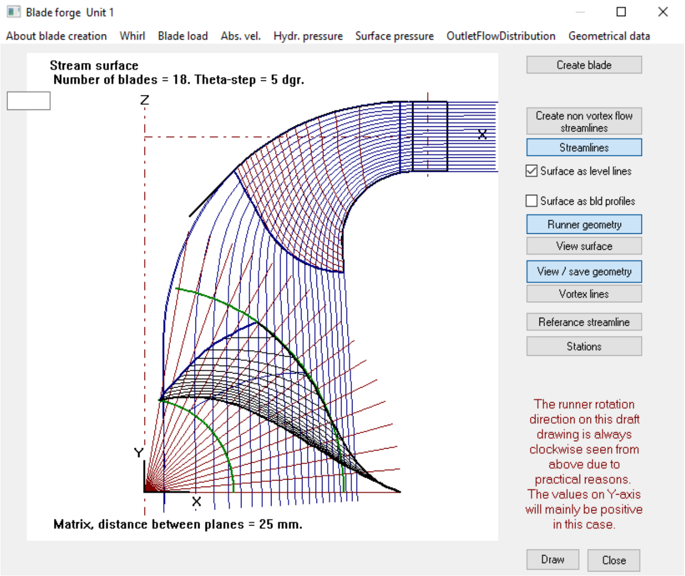


Stream surface – Blade surface

It is also important to notice that the final runner blade geometry deviates from the mean stream surface.
An input parameter, "Blade load, outlet, mwc" is included in the blade definition function. This parameter will "lift" the outlet section of the runner blade to compensate for angle deviation due to blade load. The effect of increased outlet blade load may be better efficiency due to reduced blade surface, but NPSH will increase.

Calculation of losses

Calculation of losses for a geometrically defined turbine could be done by a CFD analyser. But the calculation time for that tool prohibits use in this case.
To reduce computing time runner blade properties as angles, areas and roughness are referenced to the mean streamline.
Effects related to number of blades are included. The Coriolis Effect is taken into consideration. Backflow is reported.

Global loss factors

All Alab elements are principally defined as Δh = f (flow, speed, level, p1, p2, p3…). The parameters p1, p2… are related to geometry. Roughness is considered as a geometrical parameter. Speed is runner speed.
But even if turbine parts are geometrically defined a specific loss factor for each part must be defined. Losses must be calibrated.
Loss distribution for prototype turbines in operation is not available, but performance curves can be used for calibration.
The performance curve is the sum of the performance or losses for all turbine parts.
To increase the statistical probability related to use of measured performance curves for defining these loss factors they are considered to be global and not related to the specific case.
This means that loss factor for turbine parts is independent of size and turbine type. These loss factors are a part of the Alab code.

Design of stationary turbine parts

Spiral case, Stay vanes, Guide vanes, Draft tube, Runner hub and ring.
As mentioned above the hydraulic efficiency is an important and critical parameter. To be able to calculate $\eta_h$all turbine parts must be geometrically defined.
Methods for designing these parts both mechanically and hydraulically are included in the creation loop. Mechanical properties influencing performance (e.g. leakage due to deflection of cover) are taken into consideration.
Hydraulic design principles for these parts are more or less similar to the design of a runner blade. Calculated losses will contribute to the determination of hydraulic efficiency.

Model testing

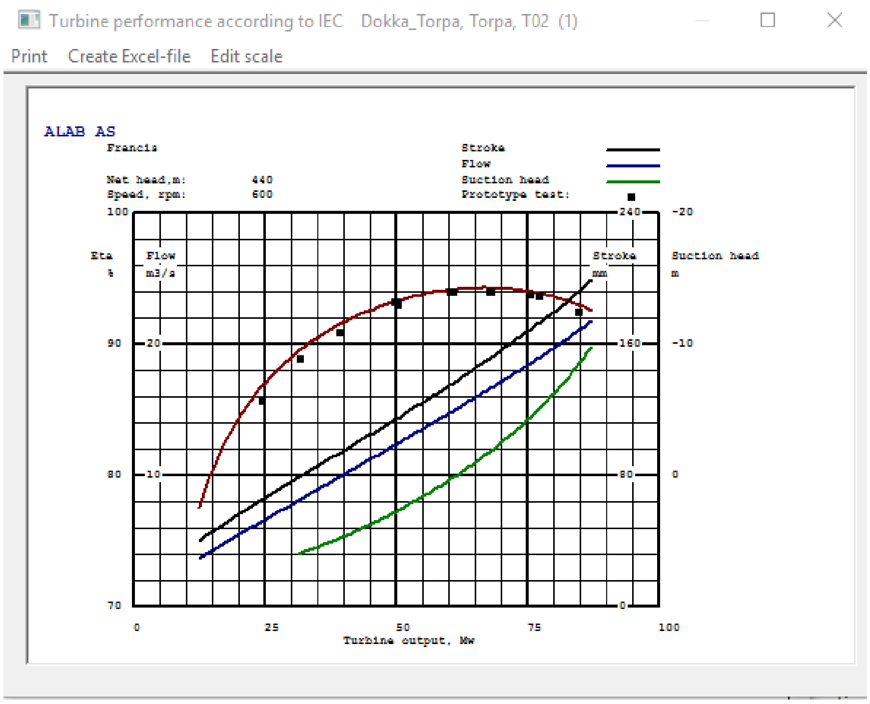
The fact that hydraulic efficiency is depending on dimensions opens for model testing. Note that the actual head for model testing normally are different from the prototype. Leakage due to deformation of stay vanes and covers will consequently influence the model efficiency.

Operation Simulation

With reference to the hydraulic principles explained above simulation is carried out by controlling turbines servo stroke. Simulation can be performed as steady state- or dynamic operation. Load rejection, load pick up or reduction gives information about speed and pressures related to the turbines but also levels, pressures and flow variations throughout the whole plant. In case of steady state operation with waterway included losses and local pressures for all plant items are calculated in addition to turbine flow, power output, efficiencies, mussel diagram and plant efficiency.

Comments

This is not a perfect solution, mainly because the mean streamline is not constant but depend on operation conditions.
But efficiency tests for prototypes shows very good agreement between calculations and site measurements. Also dynamic operation as load rejections and operation with governor confirm this method.



Epilogue

The last year's hydraulic design of Francis turbines has got high attention due to severe operational problems for several power plants with different turbine suppliers.
High head Francis turbines have been pinned as a particular problematic case.

Related designers rely on a CFD-analyser starting with a defined existing data model. This model is modified to meet specifications. Next step is model-testing in a laboratory to confirm calculations. Efficiency is measured and displayed as a mussel diagram.
Prototype efficiencies are scaled according to IEC recommendations.
This process has not been able to detect all relevant and critical properties. It is reason to believe that also low head Francis turbines may suffer from this weakness.
Alab calculates the mass and inertia for runner components hub, ring and blades. Writing an application calculating vibration frequency based on available is a rather trivial task.

ALAB March 2017.
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