Hydrodynamic design of axial hydraulic turbines

DANIEL BALINT
Eftimie Murgu University of Reşiţa
Faculty of Engineering - CCHAPT
P-ţa Traian Vuia 1-4, RO-320085 Reşiţa
ROMANIA
daniel.balint@gmail.com

VIOREL CÂMPIAN
Eftimie Murgu University of Reşiţa
Faculty of Engineering - CCHAPT
P-ţa Traian Vuia 1-4, RO-320085 Reşiţa
ROMANIA
v.campian@uem.ro

Abstract: This paper presents a complete methodology of the hydrodynamic design for the runner of axial hydraulic turbines (Kaplan) using the finite element method. The procedure starts with the parametric design of the meridian channel. Next, the stream traces are being computed in the meridian channel using the finite element method. The finite element method is implemented numerically in an original software called *QTurbo3D*. The last stage is to design the runner blade using *Q3D* techniques.

Key–Words: design, axial hydraulic turbines, meridian channel, runner blade, *QTurbo3D*

1 Introduction

The hydrodynamic design of the hydraulic turbines should be ourdays fast enough to obtain a blade pattern for the optimization. Even if a reliable optimization procedure will adjust the runner blade surface, the time spent to converge to a suitable blade depends on the first guess of the blade made in the design.

The hydrodynamic design of the runner blade is performed usually with *Q3D* techniques and next the blade hydrodynamics is computed with 3D codes as presented in [1] and [2]. The parametrization of the runner blade surface is directly linked to the speed of the optimization loops and also to its numerical convergence as presented in [3].

A procedure of the hydrodynamic design and optimization of hydraulic turbines is presented in [4] where an original software called *TurboCADoptim* is developed. The software *QTurbo3D* is based on the design ideas of *TurboCADoptim*, but other powerful numerical techniques are being employed. Also special programming tools like *numpy* and *psyco* of *Python* programming language are used for having a faster computing time. For having a friendly acces to the code, an original graphical user interface is developed in *Qt4* library and next it is translated to *Python* programming via *PyQt4* tool.

The first part of the hydrodynamic design of the runner of axial turbines is to design the hydrodynamic meridian channel. For this, a fast and reliable technique of parametrization is used as presented in [5]. Next the stream traces are computed in the 2D axisymmetric meridian channel of the turbine. For this part, a finite element method presented in [6] is employed. The last part is to design the runner blade surface and to assure a smooth three-dimensional link between the designed foil cascades.

2 Meridian channel design

The hydrodynamic design of the meridian channel is based on the design guidelines presented by Wu in [5], chapter 12. A special graphical user interface has been developed in *QTurbo3D* as shown in Fig. 1.

The design starts from the head *H* and power *P* of the turbine. With these, the specific speed is:

\[
n_s = \frac{21447}{\sqrt{H + 10}} - 924
\]

and next the speed of the runner becomes:

\[
n = \frac{n_s H^{5/4}}{\sqrt{P}}
\]

The speed of the runner should be adjusted to a synchronous one linked to a particular electrical pole pairs *p e* as:

\[
n = \frac{3000}{p e}
\]

The discharge of the turbine is computed as:

\[
Q = \frac{P}{\rho g H}
\]

where *ρ* is the density of the water and *g* is the gravity.

The peripheral velocity coefficient is:

\[
k_{uR} = 0.90163 + 0.001414 n_s
\]
Figure 1: Parametric design of Kaplan hydraulic turbines

Figure 2: Building the meridian channel of the hydraulic turbine
and then the diameter of the runner becomes:

\[ D = k_u R \sqrt{\frac{2gH}{n\pi}} \]  \hspace{1cm} (6)

The relative hub diameter is:

\[ \nu = 0.2718 + \frac{83.2338}{n_s} \]  \hspace{1cm} (7)

The number of the blades in the runner equals to 8 for heads greater than 35m, 4 blades if the head of the turbine is less than 18m and in the rest of the head range the runner contains 6 blades. The distributor height is usually 40% of the runner diameter while the relative runner depth is 21% of the runner diameter.

The hub curve is as follows (relatively to the runner diameter):

- height of the sphere over the runner shaft is 5%.
- elbow radius is 50%.
- the ogive radius is 60%.
- the ogive length is 90%.
- the ogive lowest diameter is 10%.

The shroud curve is as follows (also relatively to the runner diameter):

- the elbow 1st center and radius is 8.1% and 5%.
- the elbow 2nd center and radius is 8.7% and 10%.
- the cone 1st and 2nd radii equal to 15.4% and 5.52%.
- the cone starts with a diameter of 98.1% and has an angle of 8.3 degrees.

The output of the meridian channel of the turbine is plot in real-time when scrolling the bar as shown in Fig. 4. The region of the stream traces in the runner part is cut off and parameterized in order to have the stream tubes for the design of the runner blade. They are transposed in coordinates and fitted with a 5th order polynomial function.

The two-dimensional axi-symmetrical flow is assumed incompressible, irrotational and inviscid. The problem formulation uses the stream function \( \psi \) where the velocities are obtained as:

\[ v_x = \frac{\partial \psi}{\partial y} \]  \hspace{1cm} (8)

\[ v_y = -\frac{\partial \psi}{\partial x} \]  \hspace{1cm} (9)

The stream function formulation \( \psi \) satisfies the 2D Laplace equation:

\[ \nabla^2 \psi = 0 \]  \hspace{1cm} (10)

The computational domain is shown in Fig. 3. The stream function \( \psi \) is constant on the hub and shroud curves, therefore \( \psi = 0 \) for the hub and \( \psi = 1 \) for the shroud respectively.

The elemental equation is:

\[ \sum_{j=1}^{n} \psi_j \int_{\Omega^e} \nabla N_i \cdot \nabla N_j \, d\Omega = \int_{S^e} N_i \frac{\partial \psi}{\partial n} \, ds \]  \hspace{1cm} (11)

where \( n = 4 \) is the number of quadrilateral element nodes.

The matrix form becomes:

\[ [E^e] \{ \psi \}^e = \{ \Psi \}^e \]  \hspace{1cm} (12)

where the element matrix and the right-hand-side terms are as follows:

\[ E_{ij} = \int_{\Omega^e} \left( \frac{\partial N_i}{\partial x} \frac{\partial N_j}{\partial x} + \frac{\partial N_i}{\partial y} \frac{\partial N_j}{\partial y} \right) \, d\Omega \]  \hspace{1cm} (13)

\[ \Psi_i = \int_{S^e} N_i \frac{\partial \psi}{\partial n} \, ds \]  \hspace{1cm} (14)

4 Hydrodynamic design of the turbine runner blade

For starting the design of the Kaplan runner blade, few parameters should be available from plant geometry or from the previous meridian channel design: the head of the turbine, the power, the runner speed and diameter together with the relative hub diameter, but also the number of blades.

The inlet and outlet velocity profiles should be delivered related to the flow produced by the distributor.
Figure 3: The mesh of the meridian channel with quadrilateral elements

Figure 4: Computing the streamlines using the finite element method
Figure 5: Designing the runner of the turbine using the Q3D technique

Figure 6: Vizualization of the designed 3D runner blade
of the one designed for the draft tube inlet. The difference between them shows the loading of the cascades, therefore a law of the radial loading distribution should be imposed. Usually, the loading at hub and shroud cascades should be decreased in order to reduce the unsteady effects due to the clearance between the hub/shroud curves and runner blade. It is known that this clearance is usually 0.1% of the runner diameter and it generates vortex ropes at off-design operating regimes.

Next, the relative chord length of the foils should be delivered (the values in the middle span section and at the hub) or they will be imposed as:

\[ (l/t)_{med} = \frac{78}{360} \]  
\[ (l/t)_{hub} = 1.1(l/t)_{med} \]

where \( z_{bd} \) is the number of blades.

The thickness function of the foils should be delivered to QTurbo3D by its maximum thickness \( d_{max} \) and the position of the maximum thickness \( x_{d_{max}} \) (the values are relative to the chord length of the foil):

\[ y_d = \frac{d_{max}}{2} \sqrt{x - x_{d_{max}}} \]

where \( y_d \) is the thickness value for a foil with unit chord length and placed originally with the leading edge in the origin of coordinate system. The coefficient \( m \) of the root in the above formula is computed in the range of \( 20 \div 60\% \) of the relative position of the maximum thickness as:

\[ m(x_{d_{max}}) = \sum_{i=0}^{4} u_i x_{d_{max}}^i \]

where the coefficients have the values \( u_0 = 10.985, u_1 = -69.7486, u_2 = 187.632, u_3 = -237.949 \) and \( u_4 = 115.706 \).

Next, the relative position of the maximum loading from leading to trailing edge of the foils should be delivered. Usually, a value of 35% is used, but it should be related also to the position of the blade axis in order to avoid torsion moments of the blade.

For this part of the hydrodynamic design of the runner blade, a graphical user interface is built in QTurbo3D as shown in Fig. 5. Then, the three dimensional blade is plot using the Gnuplot library as presented in Fig 6.

5 Conclusion

This paper shows a method to employ the finite element method in the hydrodynamic design of the runner of axial turbines. The finite element formulation presented in [6] is implemented in an original software QTurbo3D developed by the authors.

The meridian channel of the turbine is meshed by quasi-linear quadrilateral elements directly in QTurbo3D and the stream traces are being computed using the finite element method (the solver is a part of QTurbo3D).

In conclusion, the design of the runner became faster and more easily to adapt in parametrical optimization procedures.

Acknowledgements: The present work has been co-funded by the Sectoral Operational Programme Human Resources Development 2007-2013 of the Romanian Ministry of Labour, Family and Social Protection through the Financial Agreement POSDRU/89/1.5/S/62557.

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