Multi-objective shape optimization of runner blade for Kaplan turbine

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Abstract. Automatic runner shape optimization based on extensive CFD analysis proved to be a useful design tool in hydraulic turbomachinery. Previously the authors developed an efficient method for Francis runner optimization. It was successfully applied to the design of several runners with different specific speeds. In present work this method is extended to the task of a Kaplan runner optimization. Despite of relatively simpler blade shape, Kaplan turbines have several features, complicating the optimization problem. First, Kaplan turbines normally operate in a wide range of discharges, thus CFD analysis of each variant of the runner should be carried out for several operation points. Next, due to a high specific speed, draft tube losses have a great impact on the overall turbine efficiency, and thus should be accurately evaluated. Then, the flow in blade tip and hub clearances significantly affects the velocity profile behind the runner and draft tube behavior. All these features are accounted in the present optimization technique. Parameterization of runner blade surface using 24 geometrical parameters is described in details. For each variant of runner geometry steady state three-dimensional turbulent flow computations are carried out in the domain, including wicket gate, runner, draft tube, blade tip and hub clearances. The objectives are maximization of efficiency in best efficiency and high discharge operation points, with simultaneous minimization of cavitation area on the suction side of the blade. Multiobjective genetic algorithm is used for the solution of optimization problem, requiring the analysis of several thousands of runner variants. The method is applied to optimization of runner shape for several Kaplan turbines with different heads.

1. Introduction
Recent developments in computational fluid dynamics, methods for the solution of optimization problems, and increasing performance of computers allow automation of the design process of hydraulic turbine runner. Nowadays runner shape optimization methods based on Genetic Algorithm (GA) [1] are being developed widely in the world [2-9]. Earlier the present authors presented multi-objective optimization method for the design of Francis turbine runner, based on 3D CFD analysis of the flow [5, 7]. In present work this method is extended to the task of a Kaplan runner optimization.
As a result of this work fully integrated software system CADRUN-opt, was created. Its general optimization procedure is presented in fig. 1.

Despite of relatively simpler blade shape, Kaplan turbines have several features, complicating the problem of optimization, in comparison to Francis turbines. These features, discussed below, explain why previously published optimization papers focused mainly to the design of Francis runner.

First, due to double-regulation system, Kaplan turbines normally operate in a wide range of discharges, thus CFD analysis of each variant of the runner should be carried out for several operation points to guarantee high turbine efficiency and fulfill cavitation requirements. In present paper efficiency and cavitation characteristics of the runner are simultaneously improved in two operation points: best efficiency point (BEP) and full load operation point (multi-point optimization).

Second, Kaplan turbine is high specific speed turbine. This feature imposes high request to the accuracy of performance prediction, especially to computation of draft tube losses. Nowadays authors use the combined method for calculation of losses in turbine flow passage. The idea of this method is that energy losses in certain components of the flow passage are calculated according to simple empirical (engineering) formulas without CFD computation, while losses in the other components of flow passage are obtained through 3D simulation of turbulent flow using Reynolds-averaged Navier-Stokes (RANS) equations with suitable turbulence model. It is commonly agreed, that losses in spiral casing and stay vanes can be adequately estimated using empirical engineering formulas for both Francis and Kaplan turbines. Moreover, these losses just slightly depend on the runner design, and thus can be estimated before the runner shape optimization. The choice of approach (engineering formulas or CFD) for calculation of draft tube losses depends on the specific speed of the turbine. It was shown previously that for low specific speed Francis turbines it is sufficient to use engineering formulas for draft tube losses [10]. This approach significantly reduces computational costs of the optimization process [5, 7]. Previous papers devoted to shape optimization of Kaplan runners [3, 6, 9] used either constant, empirical or pre-calculated dependencies of draft tube losses on the profile of runner outlet velocity. These approaches rely on the hypothesis that in operating points of envelope performance diagram draft tube losses are low and independent of the runner shape. Small number of parameters representing the velocity profile, namely 2 in [6], not covering all possible variations of the velocity profile behind the runner, indicate the shortcomings of this approach. Our former

Fig. 1. Optimization procedure of CADRUN-opt.
investigations showed that for accurate prediction of Kaplan turbine efficiency and position of BEP in plane \((Q_1, n_1)\) it is necessary to perform CFD computations with draft tube included in computational domain. Thus in the present paper energy losses in distributor, runner and draft tube were directly calculated using 3D hydrodynamic simulation. It should be noted, that last time Francis turbine optimization in CADRUN-opt is also done with draft tube included into computational domain for high accuracy of efficiency prediction.

Next specific feature of Kaplan turbines is the presence of gaps between blade and hub, and between blade tip and runner chamber. These clearances have a significant impact on the velocity profile at the inlet of draft tube and accordingly draft tube losses. Therefore efficiency computation of Kaplan turbines should account the flow in the gaps. This requirement significantly complicates automatic generation of computational mesh in runner domain and also increases computational costs for CFD analysis of runner geometries during the optimization process. Nevertheless, in present paper optimization of Kaplan turbines is carried out with hub and tip clearances included into the computational domain for CFD analysis of each runner geometry.

Therefore, all the specific features of Kaplan turbine are taken into account in the present optimization technique. The method is successfully applied to runner design of several vertical and horizontal-shaft Kaplan turbines with different heads. Some of the results are presented in the paper.

2. Blade parameterization of Kaplan runner
Preliminary step of solution of shape optimization problem is geometric parameterization. In the present paper only the blade surface is varied, while hub geometry remains unchanged. On one hand, parameterization of shape of runner blade should provide flexible variation of geometric shape of the blade. On the other hand, parameterization should contain as small set of parameters as possible, in order to reduce the number of trials in process of searching the best ones. Modified parameterization of shape of Francis turbine runner blade was adapted for Kaplan runner blade. Blade surface of the Kaplan runner is represented as:

\[
\mathbf{r}_{\text{blade}}(u,v) = \mathbf{r}(u,v) + d(u,v) \cdot \mathbf{n}(u,v), \quad (u,v) \in [0,1],
\]

where \(\mathbf{r}(u,v) = \{R(u,v), Z(u,v), \Phi(u,v)\}\) is the camber surface represented in cylindrical coordinate system, \(d(u,v)\) is the thickness distribution function, \(\mathbf{n}(u,v)\) is the unit normal vector to camber surface. Modification of shape of runner blade can generally be performed by variation of camber surface and thickness distribution. Only the camber surface is varied in the present paper. This is achieved by:
- variation of angular coordinate \(\Phi(u,v)\);
- variation of meridian (RZ) projection of camber surface.

Variation of angular coordinate \(\Phi(u,v)\) is similar to that, proposed previously for Francis runner [5, 7]. It should be noted that relative parameterization is used for \(\Phi(u,v)\). Not \(\Phi(u,v)\), but its deviation from the initial surface

\[
\Phi(u,v) = \Phi(u,v) - \Phi_0(u,v)
\]

is subject to parameterization. This allows variation of any complex surface with small set of geometrical parameters. Thus modification of Kaplan turbine runner is performed by variation 24 geometrical parameters: 16 angular and 8 responsible for RZ projection (fig. 2). Each runner geometry is fully represented by vector \(\mathbf{x} = (x_1, \ldots, x_{16}, x_{17}, \ldots, x_{24})\).
3. Numerical method and boundary conditions
During the optimization CFD analysis of flow inside the turbine is performed for each runner modification. Steady state flow field computations are carried out in the domain, consisted of distributor, runner with hub and tip clearances, and draft tube.

Flow in turbine is described by Reynolds Averaged Navier-Stokes (RANS) equations closed by standard k-e turbulence model. Fluid flow equations are solved numerically using artificial compressibility method. In pseudotime equations are marched using implicit finite volume scheme. Third order accurate MUSCL scheme is used for discretisation of convective terms, while 2nd order central difference scheme is used for viscous terms. Linearized system of discrete equations is solved using LU-SGS iterations. For more details reader is referred to [5, 7].

Periodic stage approach is used for the turbine flow analysis, requiring computations only in one wicket gate channel, one runner channel with 3 gaps regions, and the whole draft tube. Mixing plane boundary condition is applied on “wicket gate – runner” and “runner – draft tube” interfaces with circumferential averaging of all flow variables (p, u, v, w, k, ε).

Computations are performed for turbine with unit diameter and head (D=1 m, H=1 m).

In the inlet of the distributor total energy of flow (equivalent to total pressure for the case of zero gravity, g=0) is set constant, equal to

\[ E_{in} = H - h_{SP}, \]  

where \( h_{SP} \) is the sum of energy losses in spiral casing and stay vanes. \( h_{SP} \) can be estimated using engineering formulas or directly evaluated for each operating point using CFD computations of spiral casing and distributor. Flow angle is also kept constant in the inlet. In the exit section of the draft tube total energy \( E_{out}=0 \) is fixed. Thus turbine head \( H=1 \) m is kept constant throughout hydrodynamic calculations. Discharge \( Q \) is not known a priori and is obtained as the result of CFD simulation. This statement of boundary conditions is convenient because it corresponds to the actual physical process and does not require renormalization of discharge and speed to locate the operation point on \((Q_{11}, n_{11})\) plane, as compared to formulation with given constant discharge.

4. Objective functionals and constraints
Efficiency and cavitation requirements to turbine runner are expressed in terms of objective functionals, to be maximized or minimized. The first objective is the turbine efficiency \( \eta \), which is calculated generally by the formula:
\[ \eta = \frac{M\omega}{\rho g Q H} \eta_m \eta_v, \quad (4) \]

where \( M \) is the computed torque on the runner shaft, \( \omega \) is the angular velocity of runner rotation, \( Q \) is the computed discharge, \( H \) is the given head, \( \eta_m \) is the mechanical efficiency, \( \eta_v \) is the volumetric efficiency. It is assumed that \( \eta_m = \eta_v = 1 \) for Kaplan turbines.

In the present paper efficiency maximization is pursued in two operation points: BEP \( (Q_{11}^{(1)}, n_{11}^{(1)}) \) and full load operation point \( (Q_{11}^{(2)}, n_{11}^{(2)}) \).

An important task of runner design is to provide the required cavitation quality of the runner. One of the approaches to estimate cavitation characteristics of the runner is based on the analysis of pressure distribution on the blade surface, calculated in frames of incompressible fluid flow model. In [11] the effect of cavitation on turbine efficiency is estimated through calculation of torque contribution from the region where pressure \( p \) is less than vaporization pressure \( p_V \). Similar approach is adopted in the present paper. It consists in minimizing the weighted relative area of cavitation \( W_{cav} \) on suction side of the blade, calculated by formula:

\[ W_{cav} = \frac{\int x dS_y - y dS_x}{\int x dS_y - y dS_x}, \quad (5) \]

where \( S_{cav} \) is the area of the region on suction side of blade, where \( p < p_V \), \( S_{suc} \) is the total area of suction side of the blade. The full load operation point is the most prone to cavitation. So, functional \( W_{cav} \) is minimized only for full load operation point.

In frames of the optimization loop fluid flow calculations in each of 2 operation points are conducted with fixed: guide vane opening \( a_0 \), blade angle \( \alpha \), unit speed \( n_1 \) and total net head \( H=1m \). Discharge \( Q_{11} \) is calculated in the process of CFD solution. Within this approach discharge through turbine with modified blade may deviate from the initial discharge given in operation point \( (Q_{11}^{(1)}, n_{11}^{(1)}) \).

In order to prevent significant drift of the discharge in process of runner modification, the following constraint is introduced:

\[ Q_{11}^{*} - \varepsilon_1 \leq Q_{11} \leq Q_{11}^{*} - \varepsilon_2, \quad (6) \]

where \( Q_{11}^{*} \) is the unit discharge in given operation point; \( Q_{11} \) is the discharge calculated for modified blade; \( \varepsilon_1, \varepsilon_2 \) are tolerant deviations. Runner variants, not satisfying the above discharge constraint are excluded from the next generation.

Possible deviation of discharge for modified runner geometries points out the evident drawback of direct efficiency maximization in full load operation point. In fact, envelope performance diagram has a significant slope in the vicinity of full load operation point, fig. 3. It can happen in the process of efficiency maximization that modified runner would give higher efficiency than the initial one, but with a discharge \( Q_{11} \), less than \( Q_{11}^{(2)} \), so that the efficiency of that modified runner would drop below the envelope performance diagram \( \eta(Q_{11}) \) of the initial blade. This undesirable situation is marked with a grey square in fig. 3. Reducing the tolerances \( \varepsilon_1, \varepsilon_2 \) can solve this problem, but it makes the constraint (6) more stiff, that can lead to degeneration of population in genetic optimization algorithm. Therefore another approach is proposed and applied in the present paper. Namely, efficiency objective functional is modified for full load operation mode. The quantity subjected to maximization is not the efficiency itself, but the excess of the computed point \( (Q_{11}, \eta) \) over the line \( m \), tangent to curve \( \eta(Q_{11}) \) of the initial runner in point \( Q_{11}^{(2)} \), see fig. 3. Note, that slope of the tangent \( m \) is estimated before the
optimization process using experimental or calculated performance curve $\eta(Q_{11})$ of the initial runner. This modified efficiency functional is called “EffSlope” in the rest of the paper.

![Fig. 3 Performance curve $\eta(Q)$ of the initial runner, used for evaluation of Eff_Slope.](image)

![Fig. 4 Dependency $W_{cav}(Q_{11})$ for the initial runner, used for evaluation of Wcav_Slope.](image)

The same situation takes place with the usage of functional $W_{cav}$ (6). Dependency $W_{cav}(Q_{11})$ has a significant slope in the vicinity of full load operation point. Therefore direct minimization of $W_{cav}$ can give runner geometry that has a reduced $W_{cav}$ but at a smaller discharge, fig. 4. In order to avoid such undesirable geometry variants, the modified functional Wcav_Slope is used instead of $W_{cav}$. The idea of WcavSlope is to maximize the distance of point $(Q_{11}, W_{cav})$, corresponding to a certain runner geometry, from line $l$, tangent to curve $W_{cav}(Q_{11})$, see fig. 4. The slope of line $l$ is determined a priori from steady state CFD computations of the initial runner at different discharges.

5. Runner optimization for Kaplan turbine of 20 m head
The above-described method was applied for optimization of shape of Kaplan turbine runner blade with head of 20 m and number of runner blades $z_1=5$. Block structured mesh for numerical simulation including draft tube and gaps are presented in fig. 5. Runner blade designed with the conventional trial and error method was selected as the initial variant.

![Fig. 5 Computational mesh with hub and blade tip clearances.](image)
Fig. 6. Propeller efficiency hill charts of the initial runner for BEP blade angle \( \phi_i = 0^\circ \) (a), and full load blade angle \( \phi_i = 15^\circ \) (b).

Before solving of optimization problem propeller efficiency hill charts of the initial runner were calculated for two blade angles: corresponding to BEP, and to full load operating point, fig. 6. The following operating points were selected for the solution of optimization problem (marked in fig. 6):

- Operating point 1: \( \phi_i = 0^\circ \), \( a_0 = 26 \text{ mm} \), \( n_{11} = 140 \text{ rpm} \) \( Q_{11} \approx 1.11 \text{ m}^3/\text{s} \) – BEP;
- Operating point 2: \( \phi_i = 15^\circ \), \( a_0 = 34 \text{ mm} \), \( n_{11} = 150 \text{ rpm} \) \( Q_{11} \approx 2.08 \text{ m}^3/\text{s} \) – full load.

Thus two-point, three-objective optimization was run using CADRUN-opt software. The objective functionals are the following:

- \( F_1 \) (Eff): maximization of efficiency in operating point 1;
- \( F_2 \) (EffSlope): maximization of efficiency in operating point 2, accounting slope of curve \( \eta(Q) \);
- \( F_3 \) (WcavSlope): minimization of \( W_{cav} \) in operating point 2, accounting slope of curve \( W_{cav}(Q) \).

Discharge constraints for operating point 1: \( Q_{11} \in [1.06, 1.17] \), for operating point 2: \( Q_{11} \in [2.03, 2.13] \). All 24 geometrical parameters were varied.

Optimization problem was solved using multi-objective genetic algorithm (MOGA), similar to that used in [2]. 25 populations, each consisted in 120 individuals, were calculated. Projections of the obtained Pareto front on planes \( (Q_{11}, \eta) \) and \( (Q_{11}, W_{cav}) \) are presented in fig. 8. Here “ 2 ” stands for operating point 2. Generally, designer selects several trade-off geometries from the Pareto front for further analysis. One of these geometries, g25-i015, is marked in fig. 7. Propeller efficiency hill charts of this geometry were calculated and compared to the initial runner in fig. 8 for \( n_{11} = 140 \text{ rpm} \) and \( n_{11} = 150 \text{ rpm} \). Comparison of low pressure areas, indicating cavitation performance, is presented in fig. 9.

From the presented results one can conclude that automatic optimization was able to increase efficiency to about 0.78% in BEP and to 0.76% in full load operating point. Cavitation quality of the blade was also improved.

An important requirement to Kaplan turbine runner design is to keep the unit speed \( n_{11} \) of BEP of the efficiency hill chart. To verify compliance with this requirement propeller hill chart of the selected g25-i015 runner was calculated for blade angle corresponding to best efficiency blade angle of the initial runner. The position of BEP is kept within 3 rpm.
Fig. 7 Projections of 3D Pareto front on planes ($Q_{11}$, $\eta_2/\eta_{initial}$) and ($Q_{11}$, $W_{cav}$).

Fig. 8 Propeller hill diagrams of initial and optimized blades for blade angles $\phi_i$, corresponding to BEP and full load operating points.

Fig. 9 Pressure distribution on suction side of initial blade ($W_{cav}=0.2892$, at the left) and optimized blade ($W_{cav} = 0.1707$, at the right).
6. Runner optimization for Kaplan turbine of 40 m head

This section presents the results of Kaplan runner optimization for turbine of 40 m head, with number of runner blades \( z_1 = 6 \). Operating points for optimization are the following:

- Operating point 1: \( \phi = 3.9^\circ \), \( a_0 = 30 \text{ mm} \), \( n_{11} = 130 \text{ rpm} \) (\( Q_{11} \approx 1.14 \text{ m}^3/\text{s} \)) – BEP;
- Operating point 2: \( \phi = 12.4^\circ \), \( a_0 = 38 \text{ mm} \), \( n_{11} = 135 \text{ rpm} \) (\( Q_{11} \approx 1.7 \text{ m}^3/\text{s} \)) – full load.

Objective functionals were assigned the same as for 20 m head runner. Discharge constraint for operating point 1: \( Q_{11} \in [1.08, 1.19] \), for operation point 2: \( Q_{11} \in [1.66, 1.8] \).

29 populations were calculated during the optimization process. Geometry g29_i013, satisfying the requirements of the designers, was selected from calculated Pareto front for further analysis. Propeller efficiency hill charts of this geometry were calculated and compared to the initial runner for \( n_{11} = 130 \text{ rpm} \) and \( n_{11} = 135 \text{ rpm} \) in fig. 11. Comparison of cavitation quality of the initial and optimized runners is presented in fig. 12. From the presented results one can conclude that efficiency in BEP was increased at about 0.15\% and efficiency for full load operating point was increased at about 0.9\%. Cavitation quality of the blade was also significantly improved. Computation of propeller hill charts showed that \( n_{11} \)-position of BEP was also kept.

![Fig. 10 Propeller hill diagrams of initial and optimized blades for blade angles \( \phi \), corresponding to BEP and full load operating points.](image)

![Fig. 11 Pressure distribution on suction side of initial blade (\( W_{\text{cav}} = 0.1187 \), at the left) and optimized blade (\( W_{\text{cav}} = 0.0277 \), at the right).](image)


7. **Conclusion.**
The method of automatic multi-point optimization of shape of Kaplan turbine runner is proposed. It is based on multi-objective genetic algorithm and steady state 3D simulations of turbulent flow for the evaluation of objective functions. The suggested technique takes into account specific features of Kaplan runner design. Runner performance in BEP and full load operating points is increased simultaneously with improving cavitation quality of the blade. Novel objective functionals allowed valid comparison of efficiency and cavitation quality for off-design operation points, where dependence of these quantities on discharge is significant. CFD analysis in computational domain including the draft tube allowed accurate evaluation of efficiency during the runner optimization.

Described method was implemented in fully integrated software system CADRUN-opt in close cooperation of institutes of Siberian Branch of Russian Academy of Sciences together with ОJSC “Power machines” LMZ. This system was successfully applied to the design of Kaplan turbine runners with different specific speeds. Implementation of CADRUN-opt software in ОJSC “Power machines” LMZ allowed to significantly simplify and automate the process of runner design. Runners designed using the presented method have improved efficiency and cavitation characteristics.

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