Design optimisation of replacement Francis runner – CFD application in an optimization algorithm.

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Abstract: As fluid-flow computerized simulation results are well verified nowadays; the problem of finding optimal shape of flow passages remains a fundamental effort of the designer. The design optimization process requires clearly defined set of target parameters as well as a proper iteration procedure, which would lead to the solution, or approach the target with acceptable proximity. This paper presents general outline of the method and an example of application

1 Preamble

Economic analysis of hydropower projects shows that cavitation coefficient (σ_r) and unit flow capacity (Q_{11}) are amongst major characteristic values, which, along with the hydraulic efficiency (η), really determine the quality of the design.
The approach presented here combines site-specific optimization criteria definition and the algorithm of searching for the solution based on Computational Fluid Dynamics (CFD) verifications. The search for solution is conducted based on virtual experiments on computer generated models ([1], [2], [3]). Commercial CFD software package CFX-TASCflow is applied, as its reliability is well known and verified by the Author through several applications. The process is based on an original approach, which includes methodology for the target performances factor definition, parametric blade shape representation, decision criteria and the directional searching method. The paper presents application of this methodology in an upgrade project, where the site-specific design target is defined as a set of parameters and the design optimization process, which leads to the acceptable solution.

2 General approach

Search for the solution, which is the runner design giving desired performances, is conducted in two stages:

Stage 1: Scanning

Procedure SCAN generates a family of possible shapes within widest possible range of admissible topologies. The CFD analysis of each is conducted and the results are analyzed in order to locate areas within the space of shapes, where the solutions could exist.

Stage 2: Local Optimization

Procedure CLIMB executes a CFD-GEO loop sequence, where the blade parameters are modified, one at the time, progressing only in the direction of improved performances. The GEO subroutine is an external, custom made computer program, which makes decision on blade shape changes and generates data files for the CFD module.

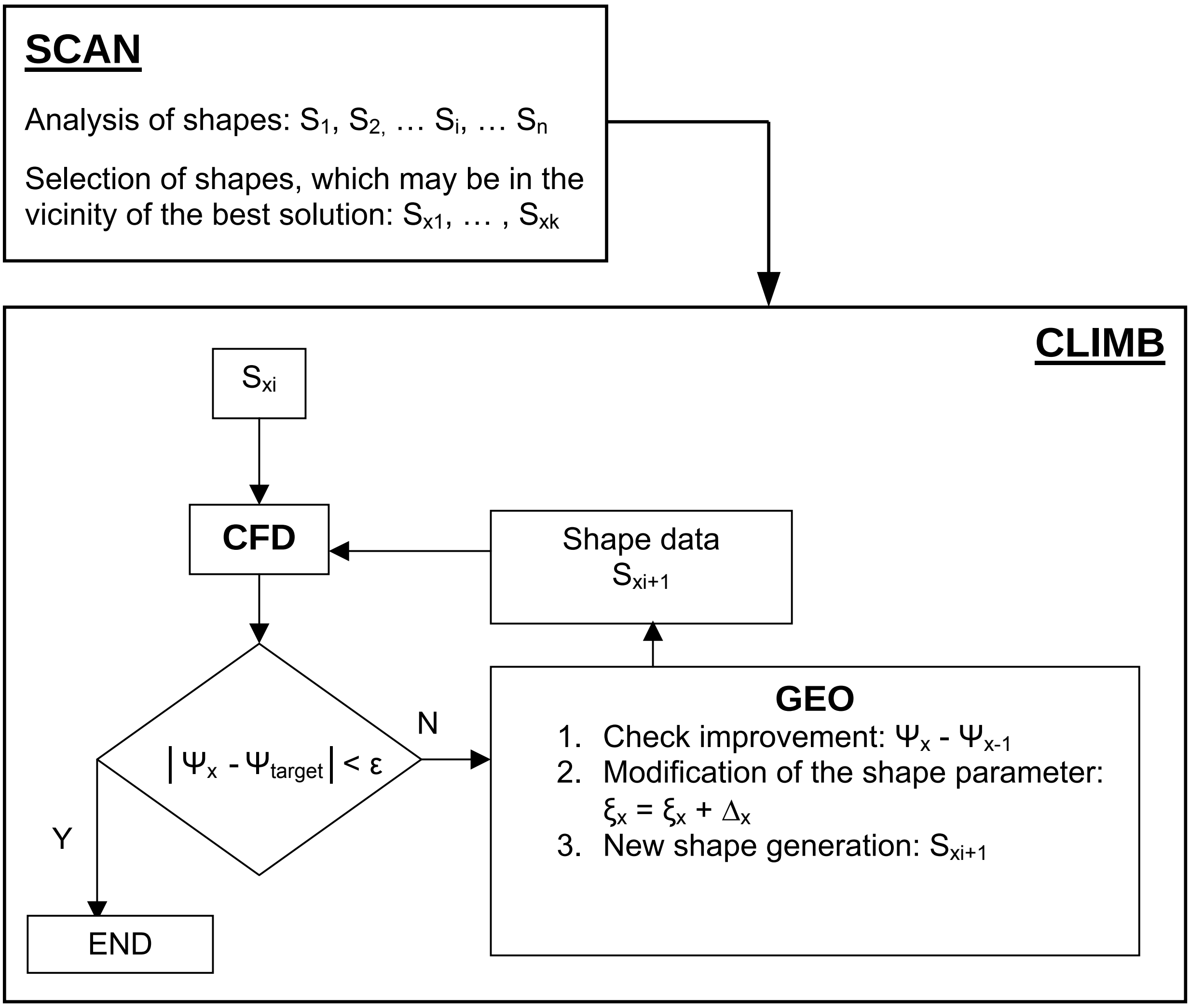


Fig. 1. Flow chart of the optimization process

Ψ_x - quality factor
ξ_x - active geometry parameter
Δ_x - rate of change of ξ_x
ε - proximity of the solution ($\varepsilon \sim \Psi_{target}/1000$)

Many automatically generated shapes are analyzed; results are stored for further analysis, to determine where may the shape of best-suited performances be. Then, the set of blades ($S_{x1}, \dots, S_{xk}$) having closest-to-the-target performances is transferred to the CLIMB procedure, which takes one of those shapes at a time as an initial guess and goes through the optimization procedure for each one separately.

The optimization procedure conducted by CLIMB exercises various blade shape modifications and accepts, at each step, for further evolution only the type of a shape change, which brings improved performances.
The final design is selected amongst the shapes optimized from each initial guess.

3 Blade shape parameterization

Selection of a blade shape description method chosen here is based on a classical notation (Fig 2), however other parameterization methods [4] are permissible and it is expected that the experience gained during applications of the presented method may trigger development and implementation of alternative modules.
The blade shape is described by the distribution of the following parameters:

A) Inlet edge
  (i) Tangent line angle (Alfa, α)
  (ii) Revolution projection outline (R2)
  (iii) Theta line (Theta, θ)
B) Trailing edge
  (i) Tangent line angle (Beta, β)
  (ii) Revolution projection outline (R1)
C) Profiles centerline curvature factor (a)
D) Profile thickness (th)

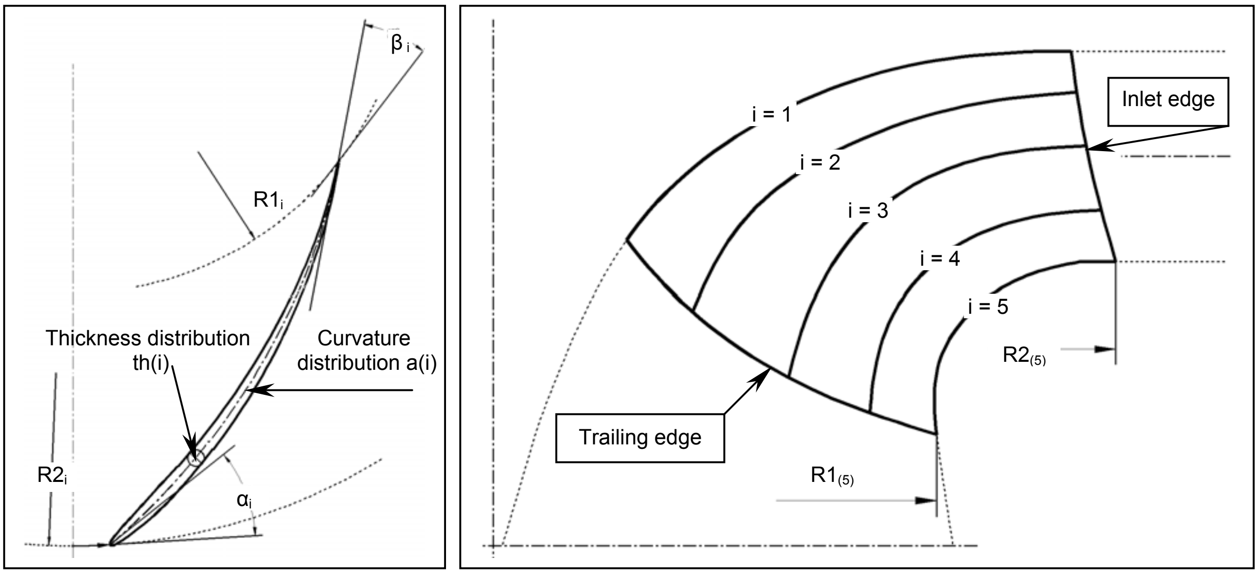


Fig. 2. Runner blade parameterization

One of specifics of refurbishment projects is that the area of investigations, in terms of shapes space, is limited by outline of existing stationary components.

Each distribution curve is modeled by the three parameters:

A – average value,
B – minimum/maximum value ratio,
C – curvature coefficient.

Each function distribution curve is therefore expressed as:

$\lambda_i = f(A_\lambda, B_\lambda, C_\lambda, i)$, where i index indicates profile number (Fig. 1), and λ_i is a value of given shape function.

For a given runner replacement project, the full set of blade shape parameters, can be presented as follows:

$$\begin{vmatrix} A_\alpha & B_\alpha & C_\alpha \\ A_\beta & B_\beta & C_\beta \\ A_a & B_a & C_a \\ A_\theta & B_\theta & C_\theta \end{vmatrix}$$

leaving total of 12 parameters, values of which will have to be found during the optimization process. It is important to notice that there are five shape functions, which will remain constant (leading and trailing edges, skirt and crown outlines as well as the blade thickness distribution).

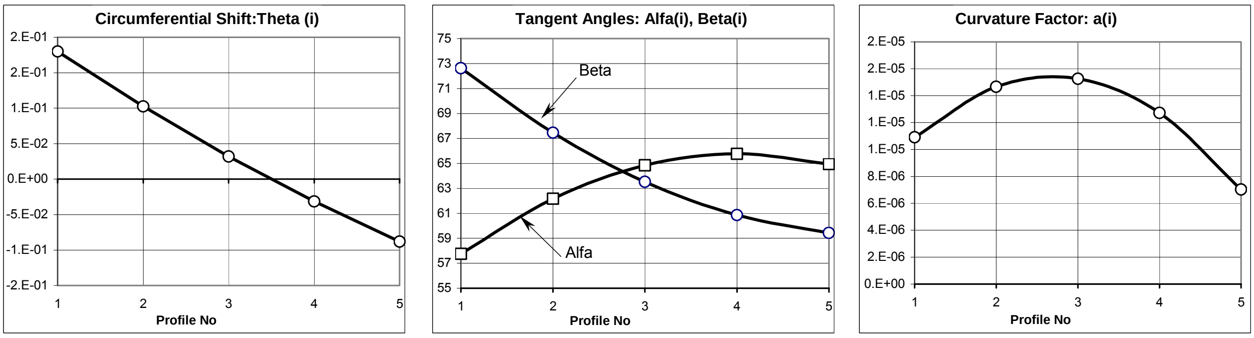


Fig. 3. Distribution of blade parameters, which are variable during the optimization process for the runner replacement project

By varying shapes of curves presented above, (Fig. 3), a subroutine within the procedure SCAN generated variety of blade shapes, examples of which are shown below (Fig. 4).

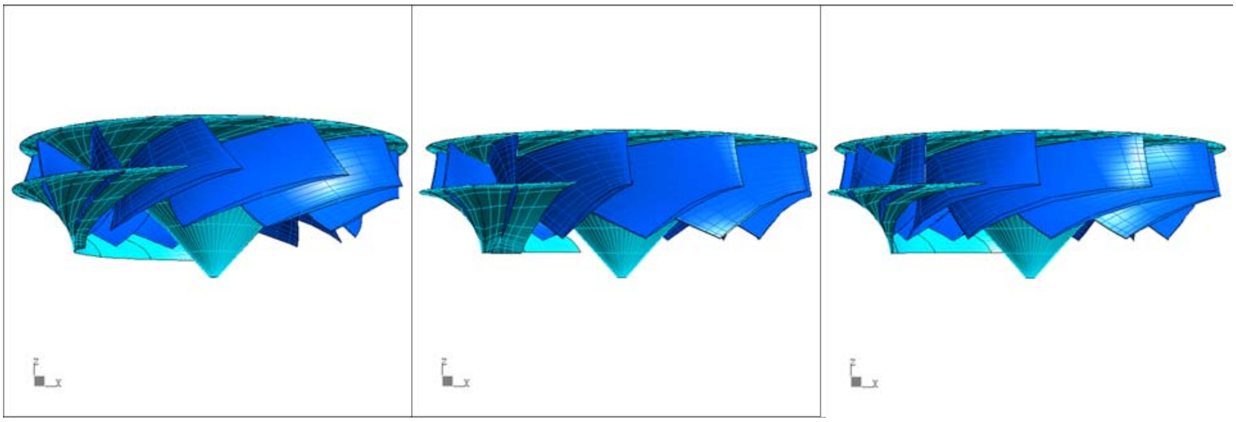


Fig. 4. Selected various blade shapes generated for the “SCAN” procedure - examples

4 Scanning

This is the first design stage, and its mission is to analyze flow through hypothetical turbines (Note: entire turbine is analyzed, including inlet casing, distributor, runner and the draft tube) equipped with different blade shapes each, which are generated within the space of permissible shapes, limited by the following constrains:

a) Parameterization method	– general outline (not all shapes are possible)
b) Topological	– limit is determined by the chosen grid topology for the CFD modeling

Based on those results, shapes giving the performances closest to the desired ones are chosen for the next stage.

Having so large amount of variables (in our case 12), the graphical representation of the distribution of benefit (function of η, Q_{11}, σ_r) becomes impossible. In order to distinguish various shapes as an option for the solution, a special function is used, which assigns a number, unique for each set of shape defining variables.

A “distance” between analyzed shapes is determined based on experiments, which had been conducted by the Author for various Francis runners. The goal is to establish such a multidimensional grid of shapes, which will not “miss” an area of potential best-suited shape.

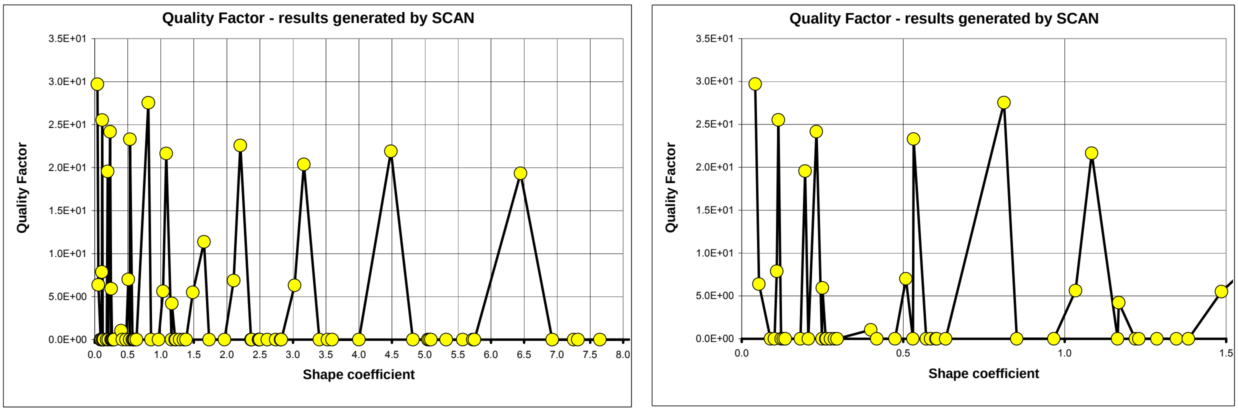


Fig 5. Results of the “SCAN” procedure; solutions, which give Quality Factor equal zero, are discounted due to back-flows in the draft tube or invalid topology

5 Climbing

The local optimization is performed in the next stage. Procedure used here performs shape modifications in the “direction” of climbing performances only.

It is achieved by trial-and-error series of shape modifications, by changes of one of 12 variables, one at the time. Each time the CFD analysis results are compared with results obtained for the previous shape and simple decision is made as to the further change of the actual variable shape parameter – if newly obtained performances are better than previous, the changes of the variable are kept the same for the next step; if not, the partial step-back is executed.

The algorithm conducts a limited series of optimization steps for each variable (shape parameter), repeating the entire series a couple of times.
A relatively long time needed to generate CFD solution becomes the most important limiting factor of the whole process. In order to shorten flow analysis time, the following was undertaken:

1) Minimization of the amount of nodes within the CFD domain -
   It may result in large discrepancy between the real flow and the results of simulation; this negative effect can be limited by refined, customized distribution of nodes.
2) Use of the previous step results as an initial guess to speed-up the convergence
3) Steady state analysis only

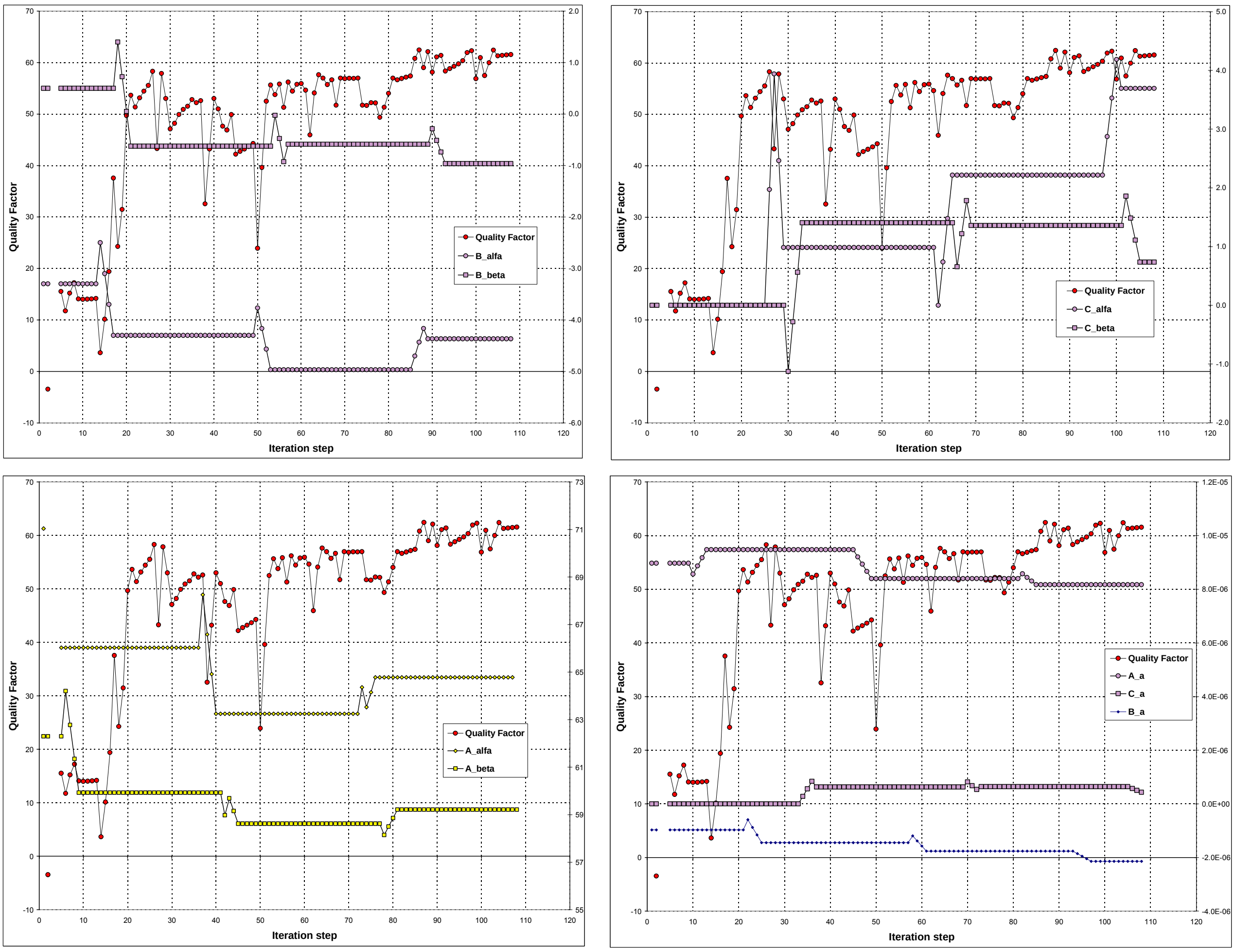


Fig 6. Illustration of searching process conducted by the "CLIMB" procedure;
Quality Factor = $\Psi = \Psi(Q_{11}, \sigma_r, \eta)$

The "CLIMB" procedure is used in two or three stages, each having larger amount of nodes and progressively larger amount of variables involved in the optimization.

6 Optimization targets

Most economically attractive refurbishments are dealing with the replacement of a turbine runner only. Existing stationary components of the turbine determine major dimensions of the runner and its general shape. Turbine setting and limits with regards to the generator power output as well as the operating range of the existing distributor determine operational limits with regards to cavitation and maximum power output. As turbine stability, hydraulic efficiency and the cavitation exposure must be communicated to the optimization algorithm, the universal target design criterion is implemented. It is worth noting that as there are other turbine evaluation criteria [5], the universal factor of the quality of the design (Ψ) described below, can include them as well.

The design target, in our case, is defined as set of the following information:

$Q_{11} = 0.49$	turbine shaft output; at maximum available wicket gate opening,
$\sigma_r <= 0.09$	incipient cavitation number, as the goal is to have cavitation-free operation; cannot be larger than the worst σ_{plant} ,
$\eta > 91\%$	hydraulic efficiency of the turbine at maximum power point as determined based on economic analysis.

Set of above listed parameters is now converted to the universal factor, which will be used by the “CLIMB” procedure as a component of an evaluation criterion:

$$\Psi_t = \left| Q_{11target} - Q_{11} \right|^{-p} * \left| \sigma_{rtarget} - \sigma_r \right|^{-s} * \left| \eta_{target} - \eta \right|^{-e}$$

where:

Ψ_t - universal factor, which represents target design criteria
P_{11} - unit power
σ_r - cavitation coefficient
η - hydraulic efficiency
$_{p,s,e}$ - coefficients ranging from 1 to 5

There is also a necessity to introduce other factor, which should represent turbine stability, for the optimization algorithm analyzes steady state only. At this point it is practically impossible, to include transient simulations within the CLIMB algorithm, due to enormous CPU time requirements.
Based on experience with practical applications, the following coefficient is used as a stability factor:

$$\Psi_s = \xi_{dt(inlet)} * \xi_{dt(outlet)}$$

where:

$\xi_{dt(inlet)} = (\mathbf{w}_{min}/\mathbf{w}_{max})_{(inlet)}$

$\xi_{dt(outlet)} = (\mathbf{w}_{min}/\mathbf{w}_{max})_{(outlet)}$

$\mathbf{w}_{min/max}$	min/max value of the axial velocity component at the sleeted section of the draft tube

Values of ‘w’, are calculated for partial sections of the draft tube to exclude influence of the boundary layer.
Therefore, due to the non-transient simplification of the optimization algorithm, the final quality criteria should combine target design criteria and the stability factor:

$$\Psi = \Psi_t \wedge \Psi_s$$

It could be combined by multiplication, or logical exclusion.
The same Factor is used to establish, which preliminary results from the “SCAN” procedures may be close to the desired solution.

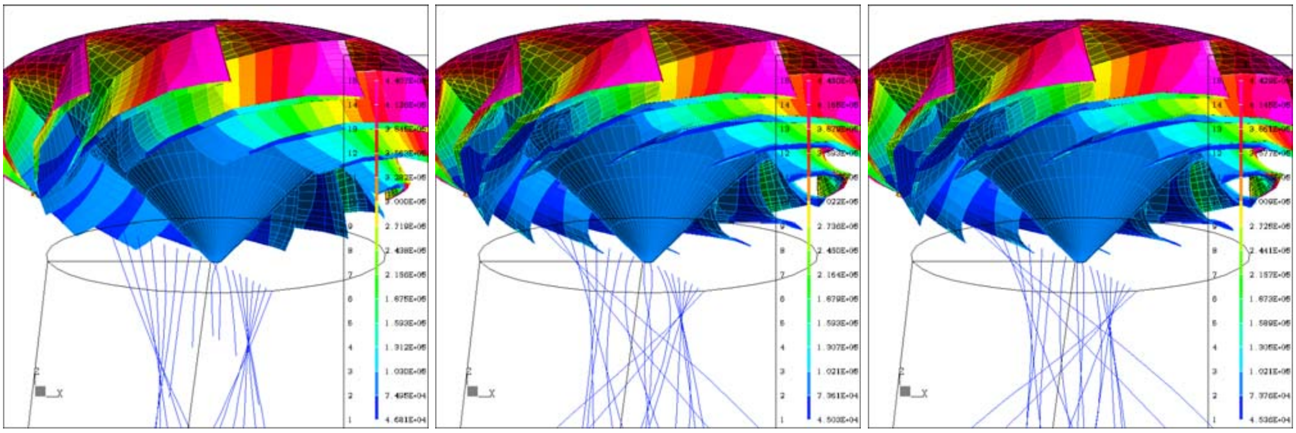
7 Results

The continuous development of the procedure involves numerous experiments to establish coefficients involved in the design quality criteria Ψ. Examples shown below represent results obtained for two different sets of values.

OPTION A

$p = 0, s = 0, e = 1$

$\Psi_s = \xi_{dt(inlet)}$
$\Psi_t = \left| \eta_{target} - \eta \right|^{-1}$



Step 0 Step 80 Step 156

Fig 7. Results of the repeatable calculations conducted by the “CLIMB” procedure

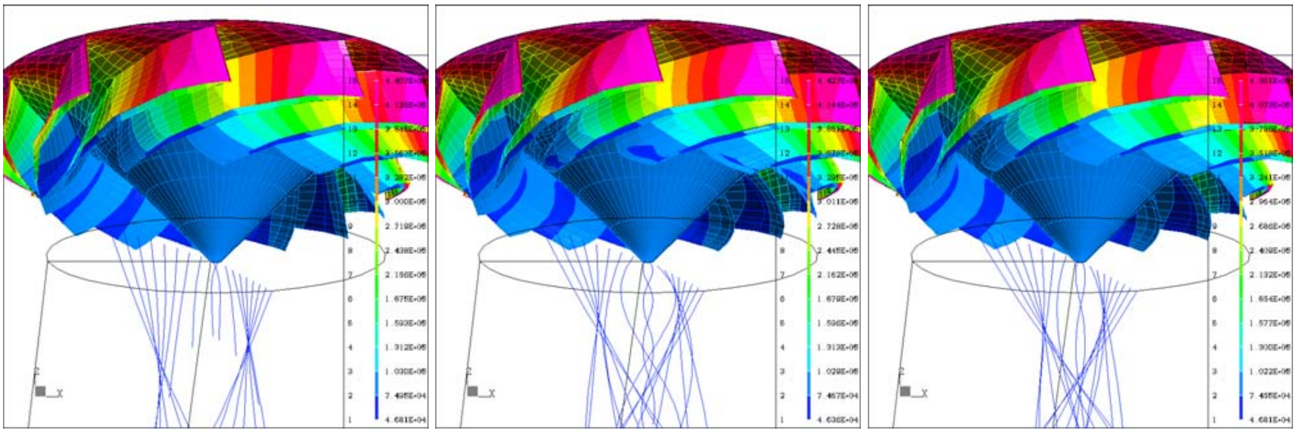
Performances achieved: $Q_{11} = 0.486$
$\eta = 90.73\ \%$
$\sigma_r = 0.101$

OPTION B

$p = 1, s = 1, e = 1$

$$\Psi_s = \xi_{dt(inlet)}$$

$$\Psi_t = \left| Q_{11target} - Q_{11} \right|^{-1} * \left| \sigma_{rtarget} - \sigma_r \right|^{-1} * \left| \eta_{target} - \eta \right|^{-1}$$



Step 0 Step 80 Step 156

Fig 8. Results of the repeatable calculations conducted by the "CLIMB" procedure

Performances achieved: $Q_{11} = 0.491$
$\eta = 91.64$ %
$\sigma_r = 0.098$

8 Conclusion

Simplified blade description, proposed and simplified CFD analysis (coarse grid, steady state) implemented in the presented method allow for reasonably fast process, which is practically used. The limited varieties of shapes imposed by its parameterization method still allow to create blade design, which reaches very good levels of turbine operating parameters, like hydraulic efficiency, cavitation coefficient and the draft tube stability. Final solution is sensitive to the definition of the universal quality function. Constant parameters included with its definition need to be refined following experimental runs. As the Author uses presented method for upgrade projects, it is expected that clearer rules would be developed within the nearest future.

9 Acknowledgment

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