Surface parameterization of a Francis runner turbine for optimum design

Author	**Firm / Institution**	**City, Country**	**Lecturer (x)**
Lluis Ferrando	*LMH / EPFL*	*Lausanne, Switzerland*	*x*
Jean-Louis Kueny	*LMH / EPFL*	*Lausanne, Switzerland*	
Francois Avellan	*LMH / EPFL*	*Lausanne, Switzerland*	
Camille Pedretti	*ALSTOM Power Turbo-Systems Technology Centre*	*Daëtwill, Switzerland*	
Laurent Tomas	*ALSTOM Hydro Tech. Centre*	*Grenoble, France*	

Abstract

The aim of this paper is to apply a surface parameterization to a blade. This geometric representation should be used as a practical tool in the process of design optimization.

Most parameterizations are based on blade section approaches. The parameters are typically angles, lengths that have a clear meaning to the hydraulic designer. Spanwise functions are sometimes used to ensure coherence between the sections and the smoothness of the constructed blade surfaces.

Here, the section-to-section approach is replaced by a purely surface method. The blade is modelled using a camber surface and thickness distributions, and the design parameters are kept as close as possible to their original physical meaning. Smooth blade surfaces are ensured, and a reduced number of variables are sufficient to describe realistic designs. The present line of research aims to introduce a surface parameterization approach, which provides a representation of the blade. One of the benefits of this methodology is the reduction of design parameters involved as this approach is no longer section dependent. Other advantages reside in the easiness to obtain smooth geometries. Finally, it is also important to point out that data exchange between programs (i.e. CAD, Mesh Generator) may now use surface representation. This entails that subjective reconstruction of this surface is no longer necessary.

As a conclusion, with our approach and the reduction of design parameters, the design optimization process becomes shorter in terms of time and effort. In this sense, preliminary tests of geometry optimization will be presented.

Résumé

Le choix du modèle paramétrique pour représenter la roue est une étape cruciale des nouvelles techniques de tracé optimal des turbines. Les techniques actuelles utilisent le plus souvent une représentation par "filets" sur des sections d'aubage. Le nombre de paramètres est alors directement lié à la paramétrisation et au nombre de filets qui dépendent de la forme, des courbures et de la régularité de la surface des aubes.

Nous proposons ici une approche basée sur la paramétrisation directe de la surface globale de l'aubage. Le modèle ne dépend plus du choix du nombre de sections et le nombre de paramètres peut ainsi être indépendant de la forme des aubages. D'autre part, il n'est alors plus utile de contrôler et éventuellement corriger la continuité entre filets, du fait du lissage automatique de la surface représentée par un modèle mathématique continu. Par cette approche, la visualisation de la surface est facilitée ainsi que le transfert vers des outils de CAO ou CFAO.

Le modèle surfacique de l'aube est intégré dans un processus d'optimisation incluant la génération automatique de maillage, le calcul CFD et l'analyse des résultats. Les premiers tests de cette procédure d'optimisation de géométrie sont présentés

Introduction

When looking at the optimization process of a runner design, one needs to consider a number of different stages. The main steps in the process that this study proposes are shown in the following flow chart (see below (Fig.1). However, there are other approaches that are also valid but not discussed in the present paper. (Ref.11).

The optimization of the whole process, portrayed in the flow chart, needs the automation of any development stage. Therefore, the runner’s development process involves: geometry generation, mesh generation, CFD computation, and Flow Analysis. In order to reduce the overall time effort of the process, each stage can be modified following different methodologies. For instance, reducing the number of design parameters, reducing the size of mesh generation, or improving optimizer’s structure and decision making, among others.

The present study focuses on the design point of view and focalises on the Geometry generation stage and the advantages of a surface parameterization. Parameterized curves have been extensively applied to the generation of new designs. The main benefit is the restrained number of parameters needed to define complex and smooth shapes. Currently, most parameterizations use Bézier and B-Splines curves to describe blade sections as geometry elements, see (Ref 1,2,3,6).

In addition, the parameterization used in by this research is based on NURBS (Non Uniform Rational B-Splines) curves -that include the previous Bézier and B-Splines curves- and surfaces for the geometry generation see (Ref 9). These curves and surfaces will be used in the preliminary tests.

With regard to other stages of the development process, the automatic mesh generation and Fluid Dynamics computation are imperative steps to determine the hydraulic performance of the generated models. To perform these stages the parameterization is linked with automatic mesh generation and fluid computation. In both steps commercial codes are employed.

Finally, to define what an "optimum design" is, it is necessary to establish the quality of the shape generated. All criteria's defining the hydraulic and mechanical characteristics to be improved in the design must be introduced in equation form (in the case of a single objective optimization process).The minimization of such an expression, "called" Objective Function, will lead us to the optimum design.

The definition of the objective function (OF) used is an aggregation function with weighted coefficients $c_{k,}$ defining the relevance factors of each single objective F_k. see (Eq. 1). ***K*** weighting coefficients $c_{k,}$, $k=1,\ldots,K$. Formulation extracted from (Ref 2).

$$F_{aggr} = \sum_{k=1}^{K} c_k F_k(\vec{x}) \qquad (1)$$

The minimization of the OF can be reached using different techniques see (Ref 1,2,) . We use global optimization algorithms based on Evolutionary Algorithms (EA) techniques to perform this minimization. At this moment, a various number of optimizers using these techniques are available. In this work different optimizers based on EA's, and improvement techniques (Artificial Neuronal Network and Response Surface) are used. These algorithms are implemented in two software packages JOE (Java Optimization Environment) and EASY (the Evolutionary Algorithms SYstem).

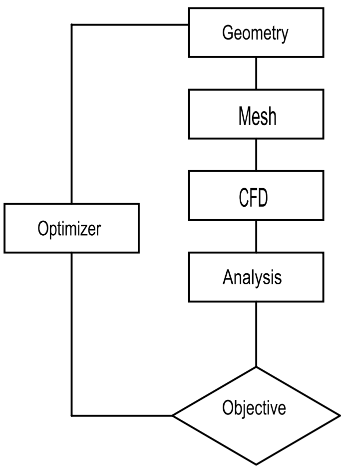


Figure 1 Optimization Flow Chart

The following points will be treated along the document:

- A brief description of the geometric entities used for curves and surface parameterization is covered.
- Then, a simple 2D application for the meridian channel parameterization and optimization will be presented.
- Finally, an approach for 3D guide-vanes and runner blades is introduced.

It is important to remark that the main research work, here exposed, is focused to obtain a reduced design variables space, enough flexible to model runner shapes. Only basic objectives functions will be used in the optimization analysis.

Geometry parameterization elements:

The use of B-Splines and Bézier curves is a powerful tool used in turbo-machinery, to describe smooth and complex shapes, the functionality and interest of this tools are well described in various articles see (Ref. 1,2,3,6) .

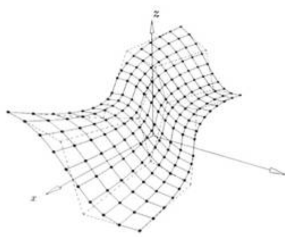
As mentioned before we base our parameterization on NURBS (Non Uniform Rational B-Splines). These entities are the most general description of any Spline form, Bézier curves and surfaces can be treated also as a subclass of the general formulation.

The following description is obtained from (Ref..9), represents the mathematical expression of a NURBS surface. The curve formulation is basically identical, though using one single parameter.

$$S(u,v)=\frac{\sum_{i=0}^{n}\sum_{j=0}^{m}N_{i,p}(u)N_{j,q}(v)w_{i,j}P_{i,j}}{\sum_{i=0}^{n}\sum_{j=0}^{m}N_{i,p}(u)N_{j,q}(v)w_{i,j}}$$

$$\{P_i\}\rightarrow Control-Pts$$

$$\{w_i\}\rightarrow Weights$$



$$\begin{matrix}\{N_{j,q}(u)\}\\ \{N_{i,p}(u)\}\end{matrix}\quad p^{th}-q^{th}\,Basis-Functions$$

Pth-qth degree basis functions!

$$N_{i,p}(u)=\begin{cases}1\_if\_u_i\le u\le u_{i+1}\\ 0\_otherwise\end{cases}\qquad N_{i.p}(u)=\frac{u-u_i}{u_{i+p+1}-u_i}N_{i,p-1}(u)+\frac{u_{i+p+1}-u}{u_{i+p+1}-u_{i+1}}N_{i+1,p-1}(u)$$

$$U=\{a,..,a,u_{p+1},....,u_{m-p-1},b,..,b\}\qquad Knot-Vector$$

$$V=\{c,..,c,v_{p+1},....,v_{m-p-1},d,..,d\}\qquad a\le u\le b\leftrightarrow c\le v\le d$$

Figure 2 Nurbs Surface Formulation

Due to the multiple interesting geometric properties and due to the fact that in manufacturing phase, the use of CAD programs becomes almost indispensable, it is very pragmatic to plan the use of such entities from the very beginning of the runner definition; consequently it is possible to keep a compact and robust description of the geometry in the whole development phase.

Flow channel approach

Before getting into the complete blade surface parameterization, we perform a 2D application for the meridian view of the runner. For this application only parameterized curves are needed.

The description of the flow channel determines the first constraints that a runner has to achieve. Usually this initial form is obtained from statistics over a large sample of installed machines; this information will determine the principal geometric parameters constraints of the channel and characterize the bounds of possible geometric configurations.

The flow channel profile is defined using the hub and shroud contours. The use of single curve for the entire definition of each contour is possible, but depending on the shape a suitable representation can require a high number of parameters, with no geometric meaning, even using parameterized curves.

In our approach the hub and shroud of any channel shape is defined using a set of concatenated curves. Some geometry constraints as (continuity, tangent, etc) can be imposed to represent feasible contours. In this case the use of 3 concatenated curves for hub and for shroud is used; this configuration presents the advantage to use a reduced number of parameters and to impose geometric constraints easily. The same idea is applied to define leading and trailing edges projections in the meridian plane. For that reason to complete a channel parameterization, the number of necessary free parameters is typically 31.

Test Example 1: Flow Channel Optimization

To perform the optimization of the flow channel, the flow chart process methodology described above is applied. The initial geometries see (Fig 3, 6) are generated as a result of setting the curve parameters. For the mesh generation stage, a simple planar structured mesh is computed along the hub and shroud contours, the number of nodes to define such mesh is commonly very limited (700 nodes are used in this case).

An inviscid flow computation through the meridian channel gives us primary information about the natural behaviour of the flow crossing the turbine channel. By this computation, we can get the distribution of velocity field in the channel. The inviscid axisymmetric flow equation using the stream function formulation is solved via a finite volume technique.

The Objective Function is selected to be the domain peak velocity, which is to be minimized. High velocity values can create unwanted behaviours as cavitations phenomena or increased power losses. High velocities regions in figures below appear in red and yellow colours, while low velocities are represented in blue.

In (Fig 3 to 5) the flow shape of a high specific speed runner is improved, the contour of the local velocity field is reduced along the shroud profile. In (Fig. 4) an intermediate-extreme generation is obtained, the higher local velocity component position can be easily located in each configuration. The number of design variables in this case was 4; the convergence optimization profile (Fig. 9) shows a decrease of 3% from the initial velocity value.

In the test case from (Fig.6 to 8), an improvement can be observed for a lower specific speed turbine design. In this example 8 design parameters were used, and the convergence chart in (Fig.10) demonstrates a 12% reduction from the initial velocity value.

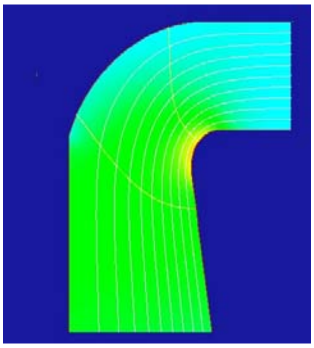


Fig 3. Initial Channel

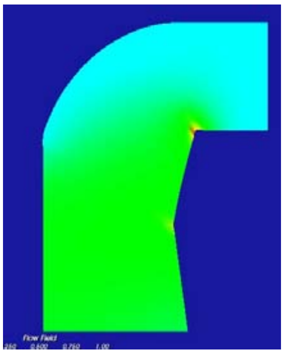


Fig 4. Generated Channel

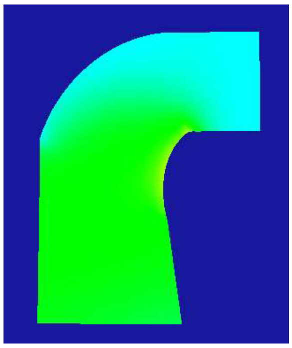


Fig5 Improved Channel

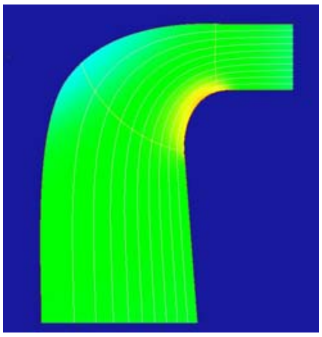


Fig 6. Initial Channel

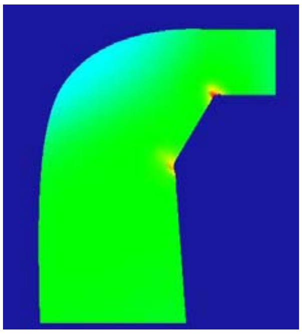


Fig 7. Generated Channel

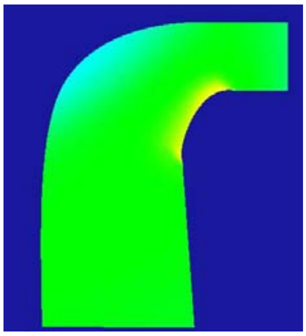


Fig8. Improved Channel

Of course, the shape optimization can not be performed over all the free geometric parameters. The selected bounds ensure the feasibility of the channel modification.

An Evolutionary Algorithm using ANN (EASY) was used to drive the optimization, in the tables below the convergence of both improvement processes are showed, objective ratio Fitness/Evaluations can be observed. The number of Evaluations is each case is 350 and 600. The estimated elapsed time to complete convergence is around 28 min for the first case and 1h 28min for the second. The configuration of the initial population is formed by 10 individuals in both cases.

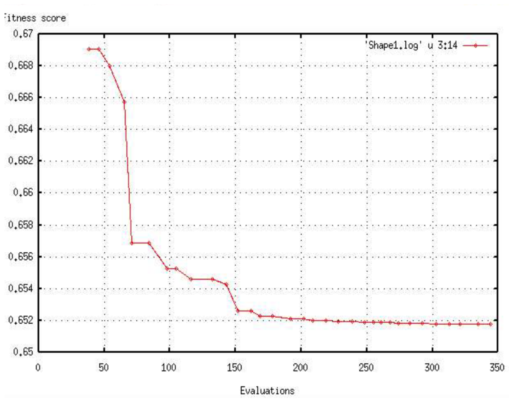


Figure 9 Fitness Convergence (Shape 1)

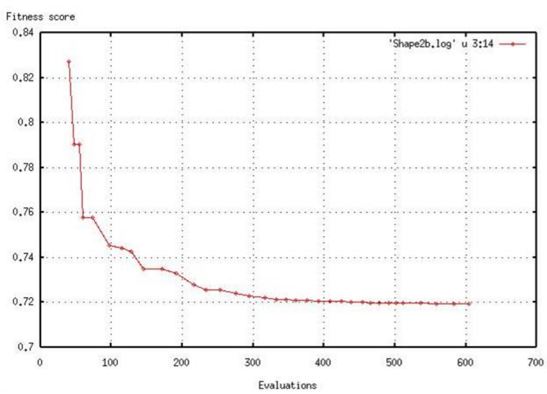


Figure 10 Fitness Convergence (Shape 2)

3D Model Approach:

To define the blade shape using surface parameterization approach, we start from the definition of a mean camber surface, defined as a "Coon's patch". This surface may contain the main shape of the blade. The Camber Surface keeps the leading and trailing edge information derived from the meridian channel, and where the inlet and outlet flow angles are imposed.

The following steps are followed:

- Form the Coon's patch in the meridian plane consisting of the leading edge, trailing edge, hub and casing boundaries.
- Deform this surface to form the 3D camber surface by moving the control points of this surface.
- Apply a thickness distribution to the camber surface; a new set of parametric surfaces, for the pressure and suction side is defined for this purpose. This distribution is independent from the camber surface itself, and the number of parameters can also be variable, depending on the thickness distribution model used.

According to the main loop described in (Fig.1), the mesh generation and CFD calculations must be automatically performed. To carry out, mesh generation and computation, commercial software is used; in this case the NUMECA software package is used.

In the next tests, a reduced size mesh of around 10.000 nodes is used to compute fluid dynamics; this limited size reduces time on mesh generation and the CFD solver computation effort. However the results might be not very accurate, the main objective of the test was not to get very fine results, but to check the parameterization features.

Test Example 2: Guide Vane Optimization

The first application of the proposed parameterization is applied to model guide-vane shape of a Francis runner turbine. The main objective in this test is to adapt the main design parameters and test the sensibility on the generation.

Detailed information about the parameterization applied can be found in (Ref 10). The original hydraulic and geometric parameters were extracted from (Ref 7 .pp. 23).

The mesh size is kept to 8.500 nodes, CFD computations are performed with a complete Navier-Stokes model and k-epsilon for turbulence. The mesh generation and CFD computation takes few minutes to be rerun.

In this test case the objective function is composed to take into account some aspects on guide-vane design. Three terms are used to define this expression.

- The first term is introduced to prescribe the outlet tangential velocity, because it is a set value given by the global turbine design.

$$F_{CU} = (CU_{out} - CU_{obj})^2 \qquad (2)$$

- The second term aims at minimizing the losses for the flow crossing such configuration and expressed as F_e.

- To assure the closure of the distributor at 0° opening, it is necessary to control the L_o (GV length). The trailing edge position is imposed at values for nominal overture and R_0 (radius of rotation centre of the GV) is left free. To introduce the constraint of the forces at closure position following regulation reasons, the R_0 position is simplified to be at half way position of the chord length. The z_0 represents the number of guide vanes.

$$F_{Ch} = (L_{Ch} - \frac{2.\pi.R_0}{z_0})^2 \qquad (3)$$

The general formulation of the Objective Function in (eq.1) includes the above terms. The convergence evolution of the given equation can be found in (Ref 11).

The flexibility of the parameterization is demonstrated in (Fig.11,12). The number of design parameters to represent the guide-vanes shape is kept constant, to describe typically the camber-surface the number of free-parameters is 32. Taking constant cross section approach, this number is reduced to 8.

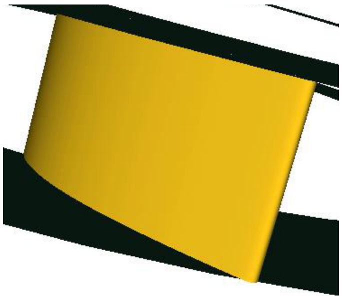


Figure 10 Cross-Section Constant

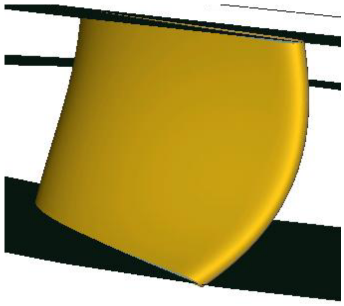


Figure 11 Cross-Section Variable

Further tests are applied to the runner blade generation; in (Fig.12 to 14) the flexibility of the parameterization is checked. It is necessary to remark that the number of design parameters for any of the given geometries from (Fig.10 to 14), is strictly the same.

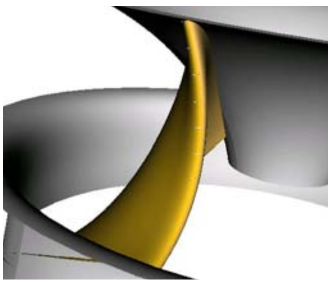


Fig. 12 Blade Example 1

Fig. 13. Blade Example 2

Fig 14. Blade Example 3

Conclusions

A surface based parameterization approach, applied to Francis turbines is exposed; the main flexibility aspects of this description are demonstrated in the joined figures. The results obtained at this moment assure the intended objectives in terms of reducing the number of parameters and keeping the required geometric flexibility to represent a wide range of runner shapes.

These results encourage the following working lines to be done on the optimization of an existing geometry. The ongoing works will be applied to the "*Gamm*" runner blade optimization. Improvements on objective functions might be done as well as the use of accurate computations to guarantee confidence in the results.

References

Ref 1 Laurent Tomas, Camille Pedretti, "Automated Design of a Francis Turbine Runner using Global Optimization Algorithms". Proceedings of Hydraulic Machinery and Systems 21st IAHR Symposium, September 2002, Lausanne.

Ref 2 Giannakoglou, K.C., "Design of Optimal Aerodynamic Shapes using Stochastic Optimization Methods and Computational Intelligence", Progress in Aerospace Sciences, 38, pp.43-76,2002.

Ref 3 R.Schilling, S.Thum "Design Optimization of Hydraulic Machinery Bladings by Multi Level CFD-Technique". Proceedings of Hydraulic Machinery and Systems 21st IAHR Symposium, September 2002, Lausanne.

Ref 4 Camille Pedretti, Laurent Tomas, "Effiency Increase of the CMA Evolutionary Algorithm through use of Gaussian Processes", International Congress on Evolutionary Methods for Design, Optimization and Control with Applications to Industrial Problems. EUROGEN 2003.

Ref 5 Quagliarella D.,Vicini A. Genetic Algorithms for optimization in Aeronautics and Turbomachinery, C.I.R.A.,Italy,2000.

Ref 6 Sallaberger M., Fisler M., Michaud M., Eisele K.,Casey M., The design of Francis turbine runners by 3D Euler simulations coupled to a breeder genetic algorithm, VA Tech Escher Wyss, Zurich, Switzerland. & Sulzer Innotec , Winthertur

Ref 7 Henry P., Calcul et trace de l'aubage de la turbine Francis. 1993

Ref 8 Sallaberger,M., Eisele, K. and Casey, M. ,2001,"Accelerated design procedure for Francis runners in rehabilitation projects", Hydropower & Dams, Issue one, pp.87-92.

Ref 9 Less Piegl, 1998, "THE NURBSBOOK", Springer-Verlag

Ref 10 Ferrando Lluis, J.L Kueny, Francois Avellan. ”Optimal Runner Design: Preliminary Tests”, ERCOFTAC: Design Optimization International Conference, Athens 30March-2April. 2004.

Ref 11 T.Aschenbrenner, A. Fernández and R.Schilling. “Numerical Optimization of Hydraulic Machinery Bladings”. Proceedings of the XIX IAHR Symposium. Singapore 9-11 September 1998.