

An Approach to automatically optimize the Hydraulic performance of Blade System for Hydraulic Machines using Multi-objective Genetic Algorithm

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Abstract. This paper presents an approach to automatic hydraulic optimization of hydraulic machine's blade system combining a blade geometric modeller and parametric generator with automatic CFD solution procedure and multi-objective genetic algorithm. In order to evaluate a plurality of design options and quickly estimate the blade system's hydraulic performance, the approximate model which is able to substitute for the original inside optimization loop has been employed in the hydraulic optimization of blade by using function approximation. As the approximate model is constructed through the database samples containing a set of blade geometries and their resulted hydraulic performances, it can ensure to correctly imitate the real blade's performances predicted by the original model. As hydraulic machine designers are accustomed to do design with 2D blade profiles on stream surface that are then stacked to 3D blade geometric model in the form of NURBS surfaces, geometric variables to be optimized were defined by a series profiles on stream surfaces. The approach depends on the cooperation between a genetic algorithm, a database and user defined objective functions and constraints which comprises hydraulic performances, structural and geometric constraint functions. Example covering optimization design of a mixed-flow pump impeller is presented.

1. Introduction

It is a great challenging task to optimize the hydraulic performance of a hydraulic machine by trial and error modifying its component geometries, because it not only requires an advanced optimization software, but also the key components of the system employed within the optimization procedure should ensure the optimization loop to work robustly, accurately and efficiently [1-3]. As design tasks are getting more and more complicated in hydraulic design process, hydraulic machine designers rely more than ever on engineering simulation software, especially computational fluid dynamics (CFD), to gain credible results in a competitive time and cost [2-4]. The most difficult task is how to automatically optimize the performance of rotating blade system and core component such as turbine runner or pump impeller which consist of a number of blades. The blade shape of hydraulic machines such as Francis turbine runners and mixed-flow pump impellers usually has sculpture surfaces feature to meet the requirements of hydraulic performances. Hydraulic optimization design for blades is an intricate task involving a number of different objectives and constraints coming from hydraulics, structure and geometry [1-4]. Although designers have already applied CFD software to assess their hydraulic designs, to more tightly integrate CFD analyses is further required in the design procedure by using efficient optimization methods to get more reliable design [2-5]. Although the CFD tools



have become more accurate, fast and user-friendly, they do not have the ability to automatically optimize the performance of a turbine runner or pump impeller. However, blade designers often begin their hydraulic designs from an existing blade and try to modify the geometric shape and improve its hydraulic performance based on a trial and error procedure. In this procedure, the blade shape is manually modified based on the designer's experience and then the flow field on the modified blade is analyzed with CFD software. As the market compel to greatly short design time schedule, it do not allow the designer to test many modifications and therefore cannot take full advantage of the huge potential and amount of information provided by the CAD, CFD and structural analysis [2-4]. For the hydraulic optimization of a hydraulic machine, the optimization of blade system is one of most difficult task, an approach to automatic hydraulic optimization combining a blade geometry parametrization generator with an automatic CFD solution process and an optimization algorithm that are suitable for hydraulic optimization of the rotating blade system inside hydraulic machines is presented and demonstrated in optimization design of a mixed-flow pump impeller in this paper.

2. Optimization strategy and procedure

2.1. Optimization strategy

To realize hydraulic optimization of a hydraulic machine's flow passage, one of most difficult task is the optimization of rotating blade systems such as pump impeller or turbine runner. Hydraulic machine designers often select the other fixed flow passages than rotating blade systems using the knowledge acquired from the previous designs or existed model with similar specific speed as the reference model, then carefully study and redesign the fixed flow passages with combination of traditional design method and CFD analysis, so that the hydraulic optimization of a hydraulic machine can firstly focus on the rotating blade system combined with the fixed flow passages with CFD analysis of whole passages. After obtained the optimized 3D geometric model of rotating blade system, we can further optimize the fixed flow passages by coupling the rotating blade system with CFD analysis of whole passages within the possible operating conditions. During hydraulic optimization of the rotating blade system, Single-object (such as efficiency, cavitation) optimization can be firstly employed to obtained a pre-optimized 3D model, then take this model as the input of multi-objective optimization.

2.2. Optimization procedure

The basic idea of the presented approach is to speed the new blade system design on the basis of the knowledge acquired from previous designs of similar hydraulic machines. As shown in Figure 1, this hydraulic optimization toolchain mainly comprises essentially of a parametric blade geometry modeler, a 3D flow simulation software including parametric mesh generation tool, a coupled CFD solver and post-processor for turbomachinery, and an efficient optimizer with multi-objective genetic algorithm (MOGA).

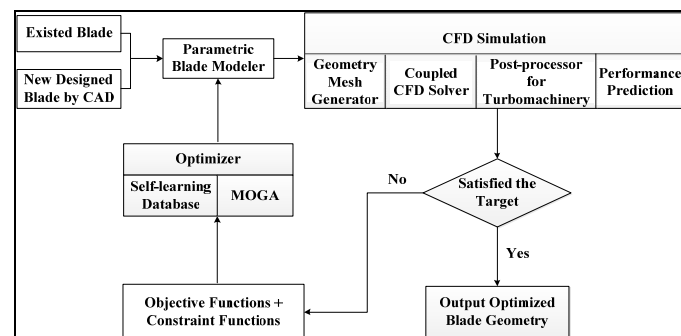


Figure 1. Hydraulic optimization loop for hydraulic machine's blades system

The initial blade model can be obtained from the new blade design with the hydraulic, geometrical and mechanical requirements imposed by the user by means of the existed blade design tool such as CFturbo®, or from the previous designs of the similar blade. The blade geometry is firstly required to be parameterized with a reliable parametric blade modeler. The second step is to construct the approximate relation between the parametric geometry and hydraulic boundary conditions, and the hydraulic performance as well. An artificial neural network (ANN) contains free parameters that have to be adapted in order to fit the database samples through "learning process". After the mapping of the database samples, the ANN can predict the hydraulic performance of blade geometries under given flow boundary conditions that are not inside the database. To implement prediction of hydraulic performance for blade systems, a speed and robustness the CFD package consisted of mesh generator, flow solver and post-processor is plugged into an optimization loop for flow simulation. The CFD package can be selected from commercial software with steady-state from the Navier-Stokes equations. The third step is to seek a new optimized geometry to be analyzed by the 3D flow simulation. It is executed by using an optimization procedure of genetic algorithm, the hydraulic performance of blade system being evaluated by means of the trained neural network. The global performance of blade system is evaluated through single-objective or multi-objective functions. In the fourth step, the new blade geometry provided by the optimizer is evaluated by ways of the flow simulation and this new sample is added to the database. Finally, the evaluated hydraulic performance is compared to the target. If this new blade geometry has not been achieved the target performance, another design iteration is started, and the same process is repeated until the new blade geometry meet the target performance is obtained. A new iteration always starts with the neural network learning. Along with the optimization design proceeds, the database grows, the approximate relation can further improved and therefore can find a better localization of the real optimum.

3. Optimization problems and Algorithms

3.1. Optimization problems for the hydraulic design of blade system

For hydraulic design optimization problems, several objectives (such as hydraulic efficiency, cavitation, pressure pulsation, pressure distribution on blade, the required performance curve, increasing head or discharge, lowering the noise etc.) and/or constraints (such as structural stress, dimensions and manufacture requirements) and a large number of design variables may be concerned. The Multi-Objective Optimization problems of hydraulic machinery can be described as:

$$\begin{aligned} & \max/\min \{z_1 = f_1(x), z_2 = f_2(x), \dots, z_q = f_q(x)\} \\ & s.t. \quad g_i(x) \leq 0, \quad i = 1, 2, \dots, m \end{aligned} \quad (1)$$

Where:

$$\{z_1 = f_1(x), z_2 = f_2(x), \dots, z_q = f_q(x)\}$$

are objective functions, $x = (x_1, x_2, \dots, x_n) \in R^n$ are design variables, $g_i(x)$ are constraint functions.

3.2. Design variables

During the hydraulic design optimization of a blade, a set of design variables that can easily define the blade shape and should have the tight relationship with hydraulic performance. As described in next section, the blade shape can be lofted by a set of 2D section curves on stream-surfaces and a parameterized thickness distribution onto the parameterized mean camber curves with the parametric blade modeller. The parametric setup employs geometries of blade profiles on each defined stream surfaces, design variables are LE and TE angles, set angles and LE radius for the blade profiles on each defined stream surfaces, and the number of blade. In the case of mixed-flow pump blade, the design variables are:

$$x = \{\beta_{i1}, \gamma_i, R_{LEi}, \beta_{i2}, N\} \quad i = 1, 2, 3, 4, 5 \quad (2)$$

Where: γ is set angle of profile on stream surface, β_1 is inlet set angle, β_2 is outlet set angle, R_{LE} is radius of Leading edge, i is the number of stream surfaces, N is numbers of blade.

3.3. Objective functions and constraints

A good design of blade system must satisfy the hydraulic performance requirements as well as the mechanical and manufacturing constraints. There are different design objectives of the detailed hydraulic optimization in different cases of hydraulic machines.

3.4. Optimization Algorithms

The goal of the hydraulic optimization is to seek the minimum or maximum of the objective functions under given constraints through the simplified analysis model. As many local optima may exist in the design space during blade optimizing process and a global optimization technique with a fast and robustness numerical optimization algorithm is accordingly required [3,5]. Genetic Algorithms (GAs) have been found widespread use in solving of hydraulic design optimization problems [3,5]. The GAs can obtain the global optimum without being trapped into local optima in Multi-Objective Optimization (MOO) problems and also accommodate any ready-to-use analysis/evaluation software as a black-box tool, such as the CFD codes used in the applications without requiring access to its source code. In fact, it is the only necessary condition that there is the availability of an appropriate evaluation software as a black-box tool by the GA and design variables and well-defined objective functions for carrying out a GA-based optimization

4. Blade geometric parameterization and approximate model

4.1. Blade geometric parameterization

The geometric parametrization is a key element in the success of the automatic hydraulic optimization for blade system. It is idealized that the parametrization of the blade geometry should be able to provide flexible variation of the blade geometric shape with as few design variables as possible. Hydraulic machine designers are used to do design with 2D sections on stream surface that are then stacked to the 3-dimensional blade geometry [6]. There are two modes to define the profile on the 2D sections, one mode constructs the profile by independent pressure and suction sides, and another mode is to firstly define a camber curve and adds a symmetric thickness to obtain the pressure and the suction sides. The leading and trail edges blade can be blunt or rounded. The meridional sweep and tangential lean of the 2D profiles stacking can be controlled independently using various types of curves and parameters. B-spline curves, or Bézier curves with an optional number of control points are adopted to construct the shroud, hub and streamlines on meridional plane.

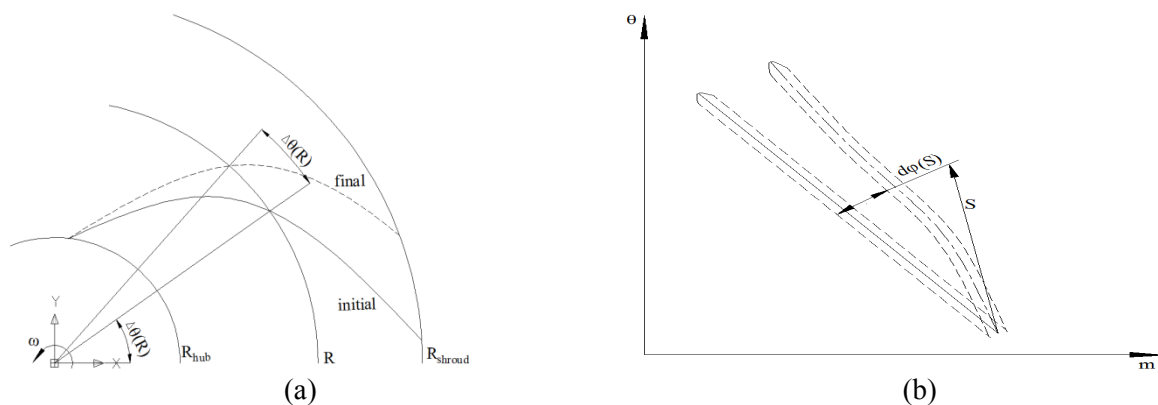


Figure 2. The parametric representation of spatial profile curves on stream surfaces: a) blade wrap

angle from leading to trailing edges and b) Spatial camber curves are mapped to a plane and added thickness during optimization.

In this paper we adopt the second mode, in design of hydraulic machine blades, a several of camber curves on stream surfaces are employed to construct the mean camber surface and control the shape of blade. As shown in Figure2(a), the spatial camber curve can be mapped to plane and camber curves on shroud and hub, mid-stream surfaces can be adjusted by Eq.(3) for the parametric representation during optimization. To add the parameterized thickness distribution on the mean camber surface, the spatial camber curves are mapped to a plane and the shape change of profiles on this plane can be defined by Eq.(4) as shown in Figure2(b).

$$d\theta(R) = \theta(R) - \theta_{initial}(R) = \frac{c_1(R - R_1) + c_2(R - R_1)^2 + c_3(R - R_1)^3}{R} \quad (3)$$

Where: all the variables defined as in Figure2(a), θ is wrap angle is radius, R_1 is the radius at the intersection between the leading edge and hub, c_1 , c_2 and c_3 are shape control parameters.

$$d\phi = \frac{c_{2i-1}(S) + c_{2i-2}(S)^2 + c_{2i-3}(S)^3}{S} \quad (4)$$

Where: $i=1,2$, $m = \int \frac{dm}{R}$, $dm = \sqrt{dR^2 + dz^2}$, $S = \sqrt{m^2 + \theta^2}$ All the variables defined as in Figure2(b)

As shown in Figure3, during the parametrization of the existed mixed-pump blade, we use 8 control points B-spline curves to construct the endwalls and streamlines on meridional plane of impeller and Bézier curves to construct the camber curves. 5 streamlines are defined linearly from hub to shroud for constructing the blade, 3D blade geometric model with NURBS can be stacked by the 5 sections using the leading and trailing edges location.

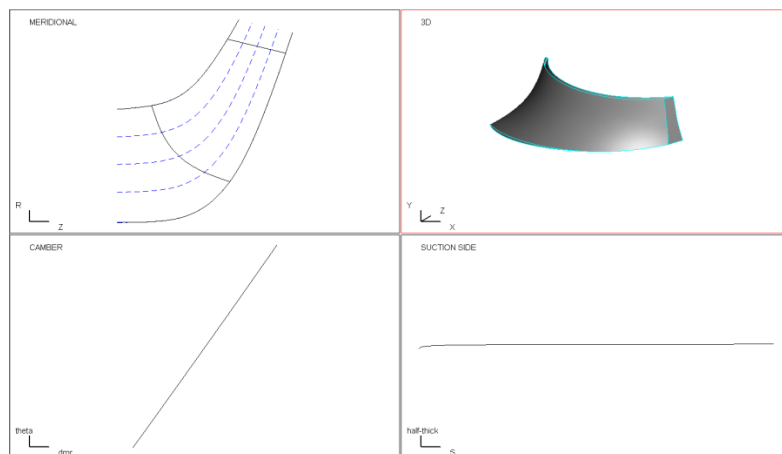


Figure 3. Initial parameterization of an existed mixed-flow blade

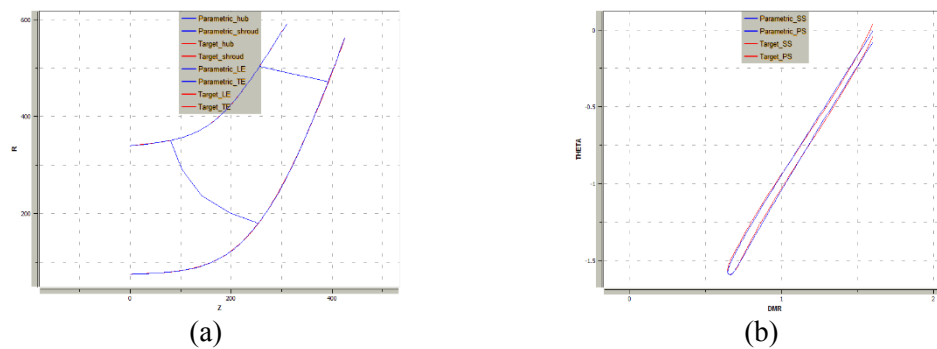


Figure 4. Comparisons between the approximate model and original model: a) Hub and shroud on meridional plane and b) Profile on mid-stream surface

4.2. Approximate model

In order to evaluate a great number of the design options, the approximate model has been employed to fast evaluate the blade hydraulic performance and as accurate as possible to mimic correctly the real blade performances predicted by the accurate model with the CFD simulation. An existed database containing several blade geometries and their associated hydraulic performances is required in this method as Genetic Algorithms employed in this solution of multi-objectives optimization. These database samples are employed to build the approximate model. Then, the optimum of the approximate model is computed by using Genetic Algorithms and, only for this sample, a CFD simulation is launched. These geometrical parameters and CFD results of this sample are stored into the database and the process proceeds. Due to the number of samples grows in the database after each optimization design cycle, the approximate model will become more and more accurate and better blade shapes can be rapidly obtained. The basic principle of this method is to construct an approximate model of the original analysis problem through CFD simulation. Then, this approximate model is able to instead of the original model inside an optimization loop. In this approach it is no longer critical because that the performance evaluation is not costly and the number of performance evaluations performed by the approximate model for the optimization. For the initial sample of optimization, the approximate model only includes the geometric parameters. As shown in Figure4, there are tiny differences between the approximate model and original model.

5. Hydraulic optimization for a Mixed-flow pump

5.1. Optimization problem of the Mixed-flow pump

Table2 shows a mixed-flow pump to be optimized and Figure5 shows the original blades and diffuser vanes. The design optimization of a pump impeller with a specific speed of $n_q = n * Q^{0.5} / H^{0.75} = 60$ and is handled as a 4-objective optimization problem. The first objective (F_{1t}) requires a maximum weighted efficiency for 5 different operating points. The second objective (F_{2t}) is related to control the $H \sim Q$ curve (to keep stability at operation in system). The third objective (F_{3t}) is to increase the weighted head for 5 different operating points without increasing the input power. The fourth objective (F_{4t}) is regarding cavitation behaviour which corresponds to control static pressure distribution on the blade surfaces, to increase the minimum pressure of impeller inlet and lower pressure pulsation inside pump.

Table 1. The specifications for a mixed-flow pump to be optimized

Head(m)	flow rate(m ³ /h)	Speed (r/min)	impeller outlet Dia.(mm)	Pump outlet Dia.(mm)	N.of blade	N.of diffuser vane	Target eff.(%)
22	6500	490	900	600	6	10	87

Table 1 shows the mixed-flow pump to be optimized and Figure 5 shows the original blades and diffuser vanes.

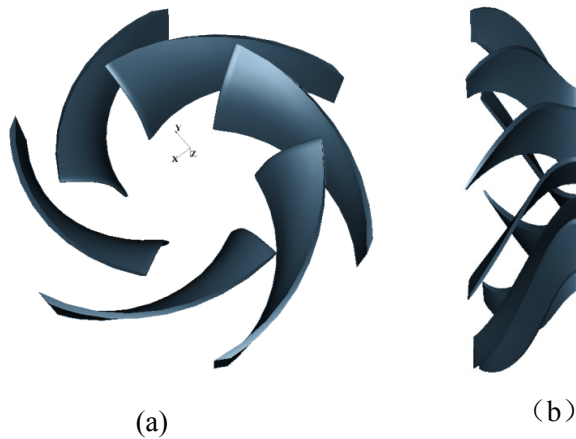


Figure 5. The three-dimensional model of mixed-flow pump to be optimized: (a) blades and (b) diffuser vanes

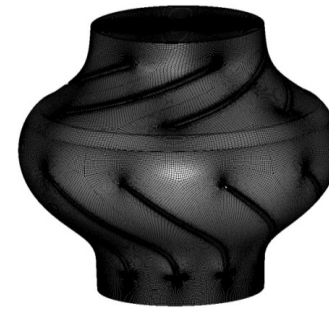


Figure 6. Mesh for flow simulation

5.2. Objective functions and constraints

In the case of mixed-pump to be optimized, the multi-objective functions can be defined as:

$$\max \{\eta(x)\}; \quad \min T_r(x); \quad \max \{p_{in}(x)\} \quad (5)$$

Where: $\eta(x)$ is hydraulic efficiency; $T_r(x)$ is input torque; $p_{in}(x)$ is average of inlet static pressure;

For this actual project, the additional objective function is $\frac{dH(x)}{dQ} < 0$ to keep the slope of $H-Q$ curve and meanwhile increase the weighted head.

Generally, 5 section profiles on stream surfaces are taken to control the shape of a blade, so there are totally 21 design variables, and constraints of design variables for the impeller blade are:

$$s.t. \begin{cases} 13^\circ \leq \beta_{i1} \leq 35^\circ \\ 22^\circ \leq \beta_{i2} \leq 36^\circ \\ 9.0 \leq R_{LE-i} \leq 10.5 \\ 53^\circ \leq \gamma_i \leq 70^\circ \\ 5 \leq N \leq 8 \end{cases} \quad (6)$$

5.3. Multi-objective and Multi-operating points' optimization

To solve the optimization problem as the described above, we employ the optimization procedure described in section 2 for Multi-objective and Multi-operation point hydraulic optimization. During optimization, the integral flow passage combining the impeller with the diffuser vanes is employed to do flow simulation. As shown in Figure 6, the mesh for flow simulation during optimization was generated with the grid generation tool matching the parametric setup of the blade geometry modeller, so that the grid can be easily aligned with the geometry. The parametric grid generator enables the use of the same mesh topology and refinement for all simulated cases.

As MOGA is employed in hydraulic optimization of blade system, database can be generated with discrete levels to keep the global of samples, 40 samples are generated and stored in the database.

Each sample includes the hydraulic performance, 21 design variables and flow data. During GA implement, Initial population was set up to 100, parent population of loop was set up to 50 and samples be set up 40. The expected hydraulic efficiency is 87% and head of pump is 25m, the max iteration steps assumed as 40 for automatic optimization.

5.4. Numerical analysis method and boundary conditions

The Spalart-Allmaras turbulence model was applied, the fluid media was water, its density is 997kg/m^3 , the characteristic length is the inlet diameter of impeller and the characteristic velocity is the inlet velocity. The mass flow-rate condition was set in the inlet, the static pressure condition was set in the outlet and the convergence precision was $1\text{E-}6$.

5.5. Optimization results and Discussion

In Figure 7, an indicative initial blade shape (solid surfaces) is compared to the final blade shape. It shows that are apparent in geometrical differences between the initial and final blades. For the final blade shape, as the geometric features have been gained by the presented optimization approach, leading to an optimal pump impeller that numerically meets all requirements set for the expected targets. Figure 8 shows the performance curves (efficiency, head and input power vs. flowrates) of the before and after optimization.

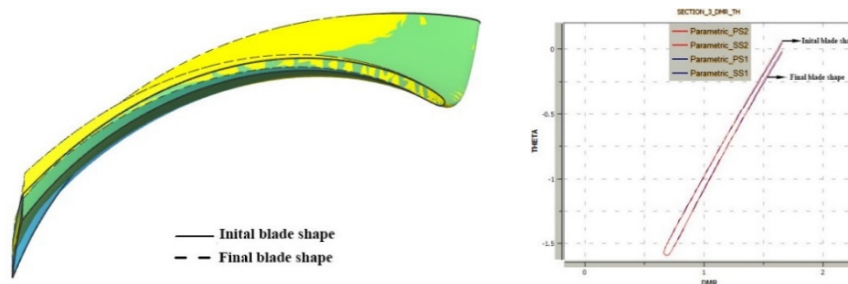


Figure 7. Initial blade shape (solid lines, green) is compared to the final blade shape (dot line, yellow)

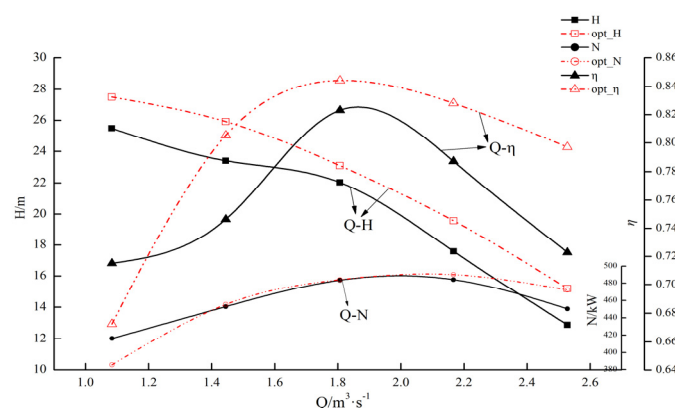
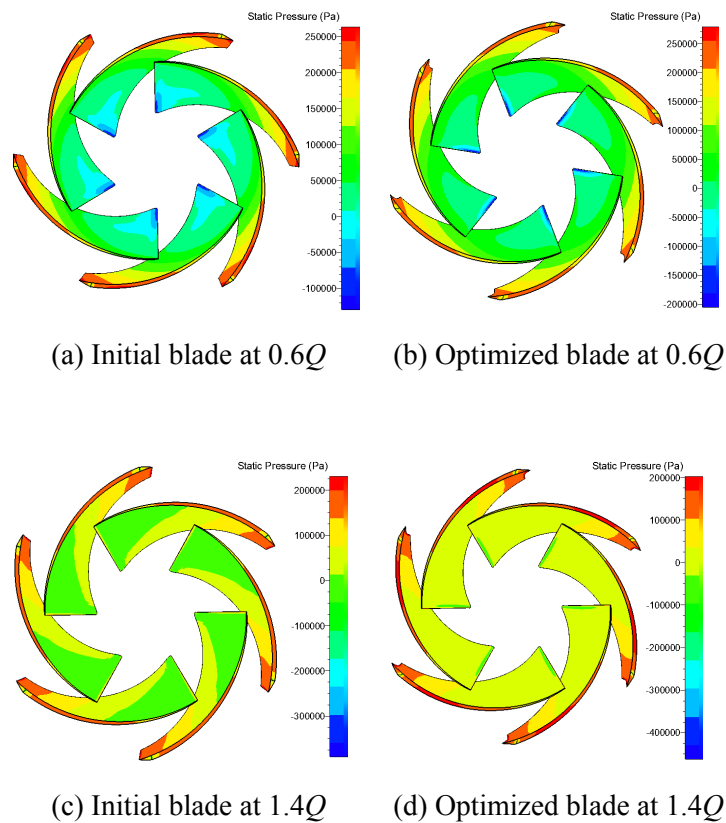


Figure 8. Performance curves of the before and after optimization.

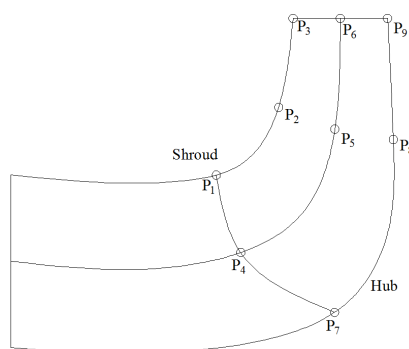
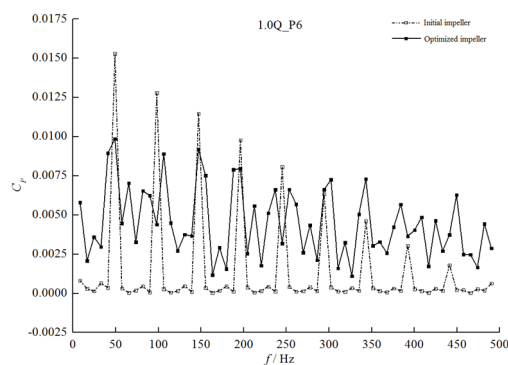
Figure 9 shows the static pressure distribution of the before and after optimization on blade surface at 3 different operating conditions, and the minimum pressure of blade inlet are listed in Table 2. It can be found that the optimized blade has great improvement in the static pressure distribution in wide operating range.

Table 2. The minimum pressure of blade inlet

	$0.6Q$	$1.0Q$	$1.4Q$
Initial blade (MPa)	-0.0496	-0.1200	0.0709
Optimized blade (MPa)	-0.0355	-0.0562	0.0871

**Figure 9.** Static pressure distribution of blade surface

In order to evaluate the safety caused by dynamic stress of blade, the pressure pulsation monitoring point was setup as shown in Figure10, and numerically computed for the monitoring point P6 as shown in Figure11 as an example, It can be found that the optimized blade has greatly decreased in the amplitude of pressure pulsation in wide operating range.

**Figure 10.** Schematic plan of Pressure pulsation monitoring points**Figure 11.** Frequency domain of monitoring point P6 at design operating point

6. Conclusion

It is a complex task to optimize the hydraulic performance because that involves many different objectives and constraints coming from various disciplines during designing of a hydraulic machine. Therefore, there is a strong need to implement automatic optimization by means of more tightly combining CFD analyses in the design chain with efficient optimization methods. The approach to automatic hydraulic optimization of hydraulic machine's blade system presented in this paper has been shown that it can obtain more efficient design processes and greatly shorten design time schedule.

- (1) To more easily establish automatic hydraulic optimization toolchain for hydraulic machine's blades system, the GA-based optimization is one of best choice. The existed or commercial software of the parametric blade geometry modeller, CFD solver including parametric mesh generation tool and post-processor for turbomachinery can be adopted to implement the relative requirements without requiring access to their source codes.
- (2) During hydraulic optimization of the rotating blade system in hydraulic machine, it is recommended that the single-object (such as efficiency or cavitation) optimization should be firstly employed to obtained a pre-optimized model and then take this model as the input of multi-objective optimization. The Multi-Objective Optimization can improve and balance the complex hydraulic performances.
- (3) In the presented automatic hydraulic optimization approach, the approximate model can be used to instead of the original model inside an optimization loop, so that the performance evaluation is not costly, and it can greatly shorten design time schedule.

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