A Novel Optimization Method for Centrifugal Blade Profile

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Abstract

This study presents a new optimization method based on genetic algorithm for the optimization of a centrifugal blade profile. As different from traditional optimization method, the hydraulic performance of centrifugal blade profile is predicted with CFD technology. The hydraulic efficiency and theoretical head are defined as objective functions for the blade profile optimization using multiobjective genetic algorithm. Three key technologies are employed as follows: (1) 3D blade profile parameterization, (2) grid generation & CFD analysis, (3) multiobjective optimization. A FORTRAN code is developed to ensure the whole optimization process running automatically. Three-order B-spline and skinning method are implemented. The control-points of the B-spline are selected as the optimization variables. Reynolds-averaged Navier-Stokes equations are solved to obtain the objective functions for generation of Pareto-optimal front. At last, a single-stage single-suction centrifugal blade is redesigned optimized at the design condition. The results show that the objective function values of maximum hydraulic efficiency and theoretical head are increased by 0.350% and 0.944%, respectively. The results also show the developed new method is an effective optimization tool for improving the blade performance.

Keywords

Impeller Profile; Genetic Algorithm; Parameterization; CFD Analysis; Multiobjective Optimization.

1. Introduction

Pumps as turbines have been successfully applied in a wide range of our daily life and industry over the world. However, research results show that the overall efficiency of pump is lower than that of other conventional turbines. Therefore, intensive researches are required to make improvement for the hydraulic performance of pump. On the other hand, tremendous developments of numerical method and computer technology have been made in the last three decades. Computational Fluid Dynamic (CFD) technique as one of the most essential tools is widely employed in the hydrodynamic design and optimization of pumps. Research results also show that the pump performance can be improved via analyzing 3D flow information obtained by CFD method. However, this method strongly depends on the experience. An effective way is to utilize optimization algorithm in a blade shape optimization. A. Jameson [1] and J. Reuthe r[2] applied a gradient-based aerodynamic shape optimization method in the design of supersonic aircraft design. But, the difference scheme for the gradient of objective functions still need to be further improved, especially for the problem with many objective functions. Li yingchen [3] developed an optimization algorithm for turbomachinery aerodynamic design through combining the continuous adjoint method with quasi-Newton method. A 2D turbomachinery blade inverse design case was presented in reference [3] based on its developed optimization algorithm. This algorithm has relative high optimization efficiency and its cost of computational resource is not significantly increase with the number of objective functions. However, it also has some disadvantages such as the implement limit of constraint condition and multiobjective optimization. E. Benini [4] presented a MGA-based (Multiobjective Genetic Algorithm) optimization for NASA rotor 37, which used isentropic efficiency and total pressure as objective functions and mass flow rate as constraint. A number of research works were done by Feng [3,5,6], who applied the

GA-based optimization method in the turbomachinery aerodynamic design. For example, Li [5] developed a new optimization method for turbomachinery. This method combines the GA algorithm with four order spline parameterize method and 2D Euler equation solving technology. Song liming [6] enhanced the efficiency of this new method by implement differential evolution algorithm and parallel compute scheme. All of above numerical study showed that the efficiency of turbomachinery can be improved via changing of blade shape. However, few reports were found about the application of centrifugal blade shape with GA-based optimization method. Recently, S. Derakhshan [7] redesign a shape of pump blades using a gradient-based optimization scheme. The optimization results showed that the pump efficiency in reverse operation was improved by blade shape modification.

This paper aims to propose a novel optimization method to optimize the centrifugal blade profile automatically. A blade profiles are redesigned using a MGA-based optimization method to pursue higher hydraulic efficiency and theoretical head. Three-order B-spline parameterization technology is employed in the optimization. The optimization program coded by FORTRAN is coupled with auto-grid and solving subroutine program to calculate 3D incompressible Navier-Stokes equations.

2. Parameterization

Several parameterizations are possible to describe the blade profile[8]. In this paper, a skinning method is realized by composing of a set of planar 2D B-spline curves in parallel plans to parameterize the 3D impeller. The parameterized blade has the advantage for hydraulic modeling requirement. This is due to each blade profile curve is a planar isoparametric curve, which can be represented by setting a corresponding parameter value. The profile can be easily changed according to the flow field characteristics through generating new parameter value of profile curve. The modified blade would be constructed by the skinning method. The blade profiles of the mid plan, hub plan and shroud plan are chosen to describe the 3D impeller blade as shown in Fig. 1 (a).

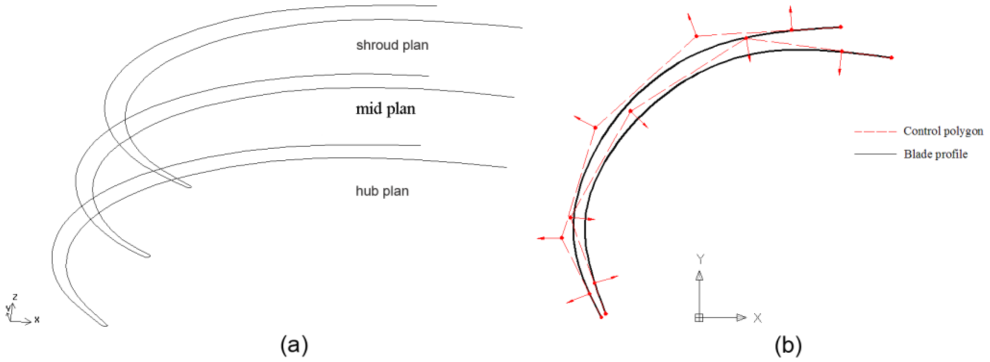


Fig. 1 Blade profiles parameterization.

(a) Skinning method for parameterization by blade profiles on the mid plan, hub plan and shroud plan.

(b) 2D three-order B-spline curve fitting the blade profiles and optimization variables distribution.

As shown in Fig. 1 (b), a 2D three-order B-spline curve[9] is used to fit the blade profiles. Similar to the algorithm used in reference [10], 7 control points are selected to obtain 81 shape points, which can describe blade profile accurately and smoothly. Furthermore, the locality of B-spline curve can enlarge search space of optimization algorithm, which is benefited to find out different blade hydraulic performance under the influence of eachy control points. Besides the leading edge point and the tailing edge point, the other five control points for each curve can be changed during the optimization process through their normal direction (as the direction of the arrow shown in Fig. 1 (b)). The distance between original position and new position of control point is defined as optimization variable, recorded as Δh. Using (x0, y0) to denote the original position, θ as direction angle of normal direction, then the new position of control point (x, y) can be described as:

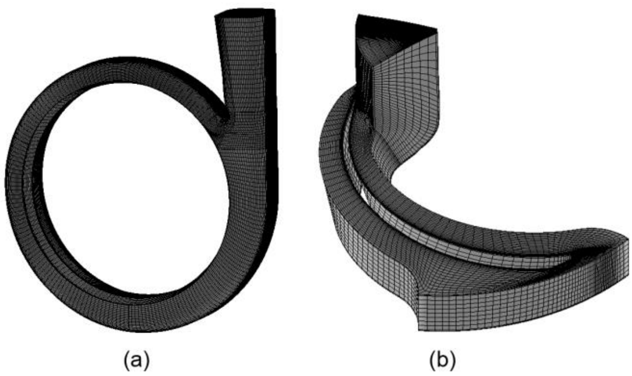
$$\begin{cases} x = x0 + \Delta h \times \cos\theta \\ y = y0 + \Delta h \times \sin\theta \end{cases} \tag{1}$$

Where the distance Δh is determined by genetic algorithm range from -5% chord lengths to 5% chord lengths, "-" denotes the opposite direction of the arrow in Fig. 1 (b).

3. 3D CFD Analysis

3D CFD analysis will be discussed in this part. AUTOGRID & FINETURBO developed by NUMECA are coupled to obtain objective functions automatically. Since present work only concern the overall performance of the centrifugal pump, the numerical method with the mixing plane model is suitable for this optimization. The computation domain as shown in Fig. 2 consists of one flow channel and volute.

3.1 Grid generation



(a) Volute. (b) Blade.

Fig. 2 Computational grid.

The Butterfly type grid and the H-O-H type grid are used to construct the volute and the blade grid, respectively. The characteristic length from solid wall to the first layer grid is set to 0.05mm, which ensures $y^+ \in [20, 50]$ to guarantee the computational accuracy in the numerical simulation [11]. The overall grid number of volute is 435844. In order to get an acceptable grid number of blade meeting the requirement both accuracy and compute resource, the numerical simulation with grid numbers 297532, 227803 and 168742 are carried out. And the maximum relative deviation of numerical results was less than 3%, then the 168742 grids are used in present simulation for blade.

3.2 Flow field computation

Table. 1 Numerical Setting

Fluid Material	Water
Turbulence Model	$k-\varepsilon$ Turbulence Model
Characteristic Length	0.41m
Characteristic Velocity	25.0m/s
Characteristic Density	998kg/m^3
Rotational Speed	1200rmp
Rotor-Stator Interaction	Mixing Plane Model
Inlet Boundary Condition	Mass Flow Rate
Outlet Boundary Condition	Static Pressure
Design Condition	59kg/s

The generated computational grids are imported in FINE for specifying the boundary and initial condition. Numerical simulation is implemented with the three-dimensional steady incompressible Reynolds-averaged Navier-Stokes equations solved by NUMECA solver. Governing equations are discretized with finite volume method and $k-\varepsilon$ turbulence model is used as a closure equations. Due to the same grid topology structure, a new blade optimization uses the original converged solution as its initial flow field. This can greatly enhance the efficiency and stability of numerical computation process.

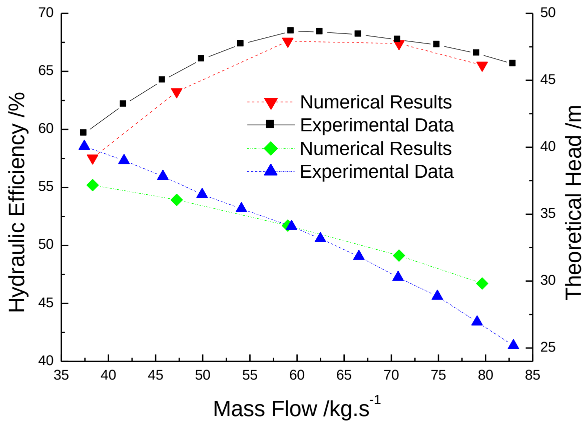


Fig. 3 Performance curve

The numerical method is validated by the pump performance experimental data. The hydraulic efficient and theoretical head for both numerical results and experimental data are present in Fig. 3. The comparison shows numerical results are good agreement with the experimental data in curve trend. The error of numerical results is comparable to the experimental data around the design condition.

4. Numerical Optimization

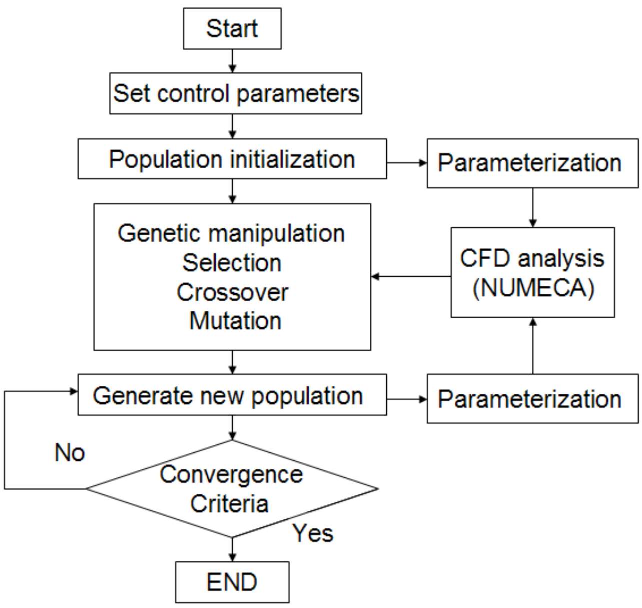


Fig. 4 Flowchart of the optimization method

Multiobjective genetic algorithm[12] is used in this paper to maximum hydraulic efficiency and theoretical head of the centrifugal pump. Since this problem involve a multitude of optimal solutions, known as Pareto-optimal front, MGA attempt to find a widely distributed set of solutions as close to the true Pareto-optimal front as possible. These approach not only provide a good idea of the extent (ideal and nadir solutions) of the true Pareto-Optimal Front but also provide information about the shape of the front [13]. Based on five typical optimization results, the optimization algorithm is composed by the Simulation Annealing Selection Operator, Simulated Binary Crossover Operator and Non-Uniform Mutation Operator. The validation of this optimization algorithm can refer to reference [14].

In this paper, the blade shape optimization problem is written as follows:

$$\text{Max}\begin{cases} F(\Delta h(i)) = [F_1(\Delta h(i)), F_2(\Delta h(i))] \\ \Delta h(i) \in [-5\%l, 5\%l] \end{cases} \tag{2}$$

$$F_1(\Delta h(i)) = \eta(\Delta h(i)) = \frac{\Delta P_{tot}(\Delta h(i)) \cdot Q}{M(\Delta h(i)) \cdot \omega} \tag{3}$$

$$F_2(\Delta h(i)) = H(\Delta h(i)) = \frac{\Delta P_{tot}(\Delta h(i))}{\rho \cdot g} \tag{4}$$

Where $\Delta h(i)$: the i^{th} control variable for the shape.

l: the chord lengths.

$\eta(\Delta h(i))$: the hydraulic efficiency.

$H(\Delta h(i))$: the theoretical head.

ΔP_{tot} : the total pressure difference between outlet and inlet.

Q : the mass flow rate.

M : the torque of blade.

ω : the angular velocity.

ρ : the density of working substance (998 kg/m^3 for water).

g : the gravity, equal to 9.81 m/s^2 in this paper.

As shown in Fig. 4, the optimization process is summarized as follows.

Input control parameters.

Provide original blade shape parameterization, grid topology structure, computed settings and initial converged solutions.

Initialize the population (shape of blades, $\Delta h(i)$) of current generation and parameterize each population.

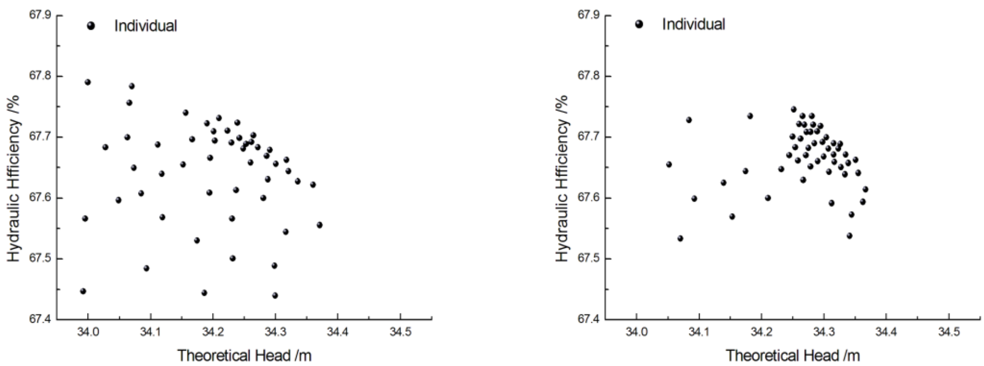
For individual $k = 1, 2, ..., k_{max}$, do CFD analysis to obtain the objective functions.

Run genetic manipulation, Selection, Crossover, Mutation.

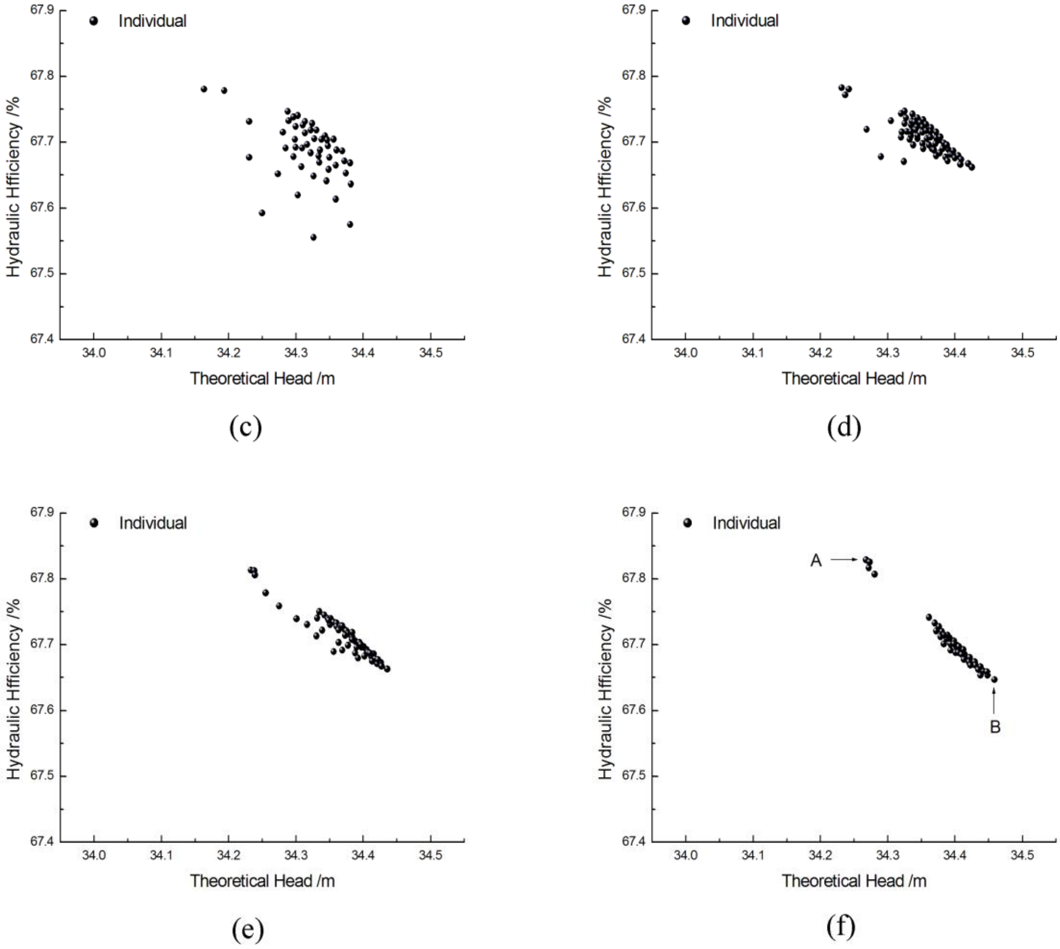
Generate new population (shape of blades, $\Delta h(i)$) and Pareto-optimal front for next generation.

Repeat step 3 to 6 until reach the maximum generation.

5. Results



(a) (b)



(a) The fifth generation. (b) The tenth generation. (c) The fifteenth generation.
(d) The twentieth generation. (e) The twenty-fifth generation. (f) The thirteenth generation.
Fig. 5 Convergence history of multiobjective optimization.

As mentioned in section 2, a 3D blade is parameterized by six 2D b-spline curves on three parallel plans. Each curve has five variable control points. The total optimization variables is 30. Population size and the largest evolution generation are set to 50 and 30, respectively. The Crossover probability equals to 100% and the Mutation probability equals to 2%. Elitist reservation strategy was used with 20% generation gap.

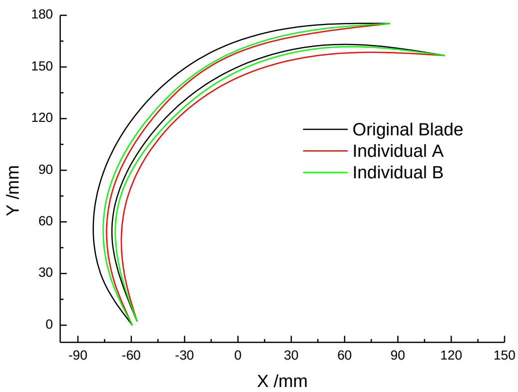


Fig. 6 Original and optimized blades on mid span

A single-stage single suction centrifugal pump, with a rotational speed of 1200rpm, mass flow rate of 59kg/s, is optimized during this process. After 30 generations of evolution, the Pareto-optimal front consist of 17 individuals is obtained. Fig. 5 shows the convergence history of multiobjective optimization. The original blade and optimal individual A and B on mid plan are presented in Fig. 6. The results show that the objective function values of maximum hydraulic efficiency and theoretical head are increased by 0.350% and 0.944% (Fig. 5 (f)), respectively.

6. Conclusion

A new optimization method was developed through combining 3D blade profile parameterization and CFD analysis with multiobjective genetic algorithm. A single-stage single-suction centrifugal pump was studied and optimized using the developed method. With no help from designers, the hydraulic performance of the optimized pump was improved through the modification of blade shape at the design condition. The maximum hydraulic efficiency and theoretical head are increased by 0.350% and 0.944%, respectively. Optimization results shows that the developed optimization algorithm is an effective way to redesign the blade shape of centrifugal pump automatically.

Acknowledgements

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References

[1] Jameson, A., L. Martinelli, and N.A. Pierce, "Optimum aerodynamic design using the Navier-Stokes equations", Theor Comp Fluid Dyn, 10(1-4), 213-237(1998).
[2] Reuther, J., et al., "Aerodynamic shape optimization of supersonic aircraft configurations via an adjoint formulation on distributed memory parallel computers", Comput Fluids, 28(4-5), 675-700(1999).
[3] Li, Y.C., D.L. Yang, and Z.P. Feng. "Inverse problem in aerodynamic shape design of turbomachinery blades", in 51st ASME Turbo Expo, Barcelona, SPAIN (2006).
[4] Benini, E., "Three-dimensional multi-objective design optimization of a transonic compressor rotor", J Propul Power, 20(3), 559-565(2004).
[5] Jun, L., et al., "Aerodynamic Optimum Design of Transonic Turbine Cascade Using Genetic Algorithms", J Therm Sci, 6(2), 111-116(1997).
[6] Liming, S., F. Zhenping, and L. Jun, "Shape Optimization of Turbine Stage Using Adaptive Range Differential Evolution and Three-Dimensional Navier-Stokes Solver", in ASME Paper GT2005-68280(2005).
[7] Derakhshan, S., B. Mohammadi, and A. Nourbakhsh, "Efficiency Improvement of Centrifugal Reverse Pump", J Fluid ENG-T ASME, 131(2), 021103-9(2009).
[8] Hoschek, J. and R. Muller, "Turbine blade design by lofted B-spline surfaces", J Comput Appl Math, 119(1-2), 235-248(2000).
[9] I.J., S., "On Spline Function", Proceeding of the National Academy of Science USA, 52(4), 947-950(1964).
[10] BC, D., "On Calculation with B-spline" J Appo Theor, 6, 50-62(1972).
[11] NUMECA, [User Manual], Vol. v7a, Brussels. 4-28(2006).
[12] Deb, K., [Multi-Objective Optimization Using Evolutionary Algorithms], Chichester, U.K: John Wiley & Sons, Chapter 2(2001).
[13] Farina, M., K. Deb, and P. Amato, "Dynamic Multiobjective Optimization Problems: Test Cases, Approximations, and Applications", IEEE TRANSACTIONS ON EVOLUTIONARY COMPUTATION, 8(5), 425-442(2004).
[14] TIAN, H., [Numerical Simulation of the Flow in Centrifugal Pump and the Blade Profile Optimization], Xi'an Jiaotong University: Xi'an, 76(2008).