Design optimization method for Francis turbine

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Abstract. This paper presents a design optimization system coupled CFD. Optimization algorithm of the system employs particle swarm optimization (PSO). Blade shape design is carried out in one kind of NURBS curve defined by a series of control points. The system was applied for designing the stationary vanes and the runner of higher specific speed francis turbine. As the first step, single objective optimization was performed on stay vane profile, and second step was multi-objective optimization for runner in wide operating range. As a result, it was confirmed that the design system is useful for developing of hydro turbine.

1. Introduction

Hydroelectric power generation is the energy that has been most widely used in the renewable energy. In the development of hydro turbine, it is necessary to optimize the hydraulic performance such as efficiency, cavitation and pressure fluctuation to meet the required specification. Recently, the hydraulic performance is evaluated by using CFD. Thanks to the development of a computing technology, it has been possible to perform design optimization combined CFD and various optimization methods. We have also developed a hydro turbine by using design of experiments (DOE) and multi-objective genetic algorithm (MOGA) as the optimization method [1] [2] [3].

In order to enhance the hydraulic performance, it is important to employ the blade design method which is highly flexible. Increasing degree of freedom expands the design space. On the other hand, the increment of design variables makes it difficult to optimize the shape. An evolutionary algorithm represented by GA is suitable to solve such hard problems, and many algorithms have been proposed. By choosing better method, shorter lead time and robustness of optimization are expected.

In this paper, new design optimization method was applied to the development of francis turbine of higher specific speed. In the design system, blade profile was defined by a flexible curve, and the optimization method adapted to Particle Swarm Optimization (PSO), which is one of the swarm intelligence techniques. As a first step, single objective optimization for stay vane was performed to confirm usefulness of the automatic design system. Next step, multi objective optimization for runner was carried out in wide operating range. In the optimization, three objective functions of efficiency and two constraint functions of cavitation are set to achieve a realistic design.

2. Methodology

2.1 Optimization method
In the development of the performance of the turbine, it is needed to consider the trade-off among the various objectives. Recently, many evolutionary algorithms, which are sophisticated optimization method, have been developed. PSO was originally developed by Eberhart and Kennedy[4]. PSO is the analogy of social behavior of bird flocking. The performances required for the optimization algorithm are the convergence of the optimization calculation, the diversity of the solution, the robustness for various problems and etc. There are many studies surveying the performance of PSO, and the excellent characteristics as the optimization algorithm were verified [5]. Since basic PSO is developed for single objective function, we employed the modified PSO which developed to apply to multi-objective optimization problems [6].

In PSO, a solution is expressed as a particle, and the population is called a swarm of particles. Each particle has position and velocity, and new position of each particle is updated by new velocity in each step. In determination of new velocity, the global best position and local best position of each particle are considered. The flowchart of the optimization system is shown in Fig. 1. The process of PSO algorithm is similar to evolutionary algorithms.

![Flowchart of the optimization system]

Fig. 1 Flowchart of the optimization system

2.2 Blade design method

In order to develop a high performance hydro turbine, it is important to employ a more highly flexible design method for the blade. In the system, blade profile is formed by Non-Uniform Polynomial B-Spline (NUPBS), and NUPBS is one kind of Non-Uniform Rational B-Spline (NURBS). It is known that the curve of the NURBS is defined by a series of control points. In NUPBS, the weight of the control points has constant value. To move those control points, the profile of curve can be modified smoothly, and the continuity of the curve is maintained curvature continuity. Moreover, the degrees of freedom can be increased by adding the control points. Fig.2 shows the blade shape definition. Blade profile and camber line are formed by NUPBS curve, and a blade surface is created by connecting several curves along the spanwise direction. To adopt the above mentioned flexible design method, improvement of the hydraulic performance associated with expansion of the design space is expected.
2.3 CFD method

In order to evaluate hydraulic performance, steady-state CFD was performed. The governing equation of flow analysis is three-dimensional Reynolds-averaged Navier-Stokes equation. And the discretization of the governing equation is done by finite volume method. Advection terms are approximated by second order upwind difference scheme. Reynolds stress is determined by RNG k-ε turbulence model.

3. Optimization results

At first, single objective optimization for stationary vanes was carried out to confirm the effectiveness of the system. The next step, multi objective and multi constraint optimization for runner was performed in wide operating range. The specification of PSO optimization is shown on Table 1. Each optimization in detail will be discussed as follows.

|                  | Stay vane | Runner |
|------------------|-----------|--------|
| Number of generation | 20        | 25     |
| Population of individual | 40        | 42     |
| Number of design variable | 23        | 27     |

3.1 Stationary vanes
3.1.1 Numerical model

The computational domain for stationary vanes is shown in Fig. 3. The flow passage composes of one pitch stay vane and guide vane with periodic boundary condition, and the cell number is approximately of 130,000. The numerical simulation was carried out at design point. Uniform flow determined by discharge and the assumed angle of incoming flow from spiral case is applied to inlet boundary condition.
3.1.2 Optimization condition

The target of the optimization is stay vane profile. The objective function is the hydraulic loss defined by the difference of total pressure between inlet and outlet. Total number of design variables is 23, which consists of parameters defining the blade camber line and profile, inner diameter, outer diameter and so on. Initial population number is 40, and those design variables are generated by random sequence. The number of generation is 20.

3.1.3 Result

The optimization history of the objective function is shown in Fig. 4. According to the figure, the relative hydraulic loss substantially becomes smaller as the design number becomes larger. The objective function improves rapidly at early generation number while there are few reasonable results in initial population which was generated randomly. The velocity distribution of optimized stay vane at turbine center is shown in Fig. 5(a), and the vector profile near the leading edge of the stay vane is shown in Fig. 5(b). These figures show that the connection between stay vane and guide vane is optimized, and the inlet angle of optimized stay vane matches to the flow angle of the incoming flow from spiral case. From mentioned above, it was confirmed that appropriate optimization results were obtained by using the automatic design system.

![Optimization history of the objective function](image1)

**Fig. 4** Optimization history of the objective function

![Velocity distribution of optimized stay vane at turbine center](image2)

**Fig. 5** Velocity distribution of optimized stay vane at turbine center
3.2 Runner

3.2.1 Numerical model

Fig. 6 shows the computational domain for runner optimization. The domain contains the flow passage of stay vane and guide vane, runner and draft tube. The numerical prediction was carried out in two steps. The cell number of runner coupled stationary vanes and draft tube is about 18,000 and 15,000, respectively.

First, the model of runner and stationary parts both with periodic boundary condition was evaluated. The coupled model is adapted since the spanwise velocity profile from guide vane is important for the optimization of runner inlet shape. The mixing plane is set at the interface between runner and stationary parts. As a next step, evaluation of draft tube was performed. Where, tangential mean velocity profile at runner outlet calculated from runner result is given as the inlet boundary condition for draft tube calculation. From the CFD results, runner head $H_r$, the hydraulic loss of stay vane and guide vane $\Delta H_{sg}$, the hydraulic loss of runner $\Delta H_r$ and the hydraulic loss of draft tube $\Delta H_d$ are obtained. The hydraulic loss of spiral case $\Delta H_{sc}$ is also calculated from 1-D calculation. Net head and hydraulic efficiency is calculated as follows formula:

$$H = H_r + (\Delta H_{sc} + \Delta H_{sg} + \Delta H_r + \Delta H_d)$$  \hspace{1cm} (1)

$$\eta_H = \frac{H}{H}$$  \hspace{1cm} (2)

Turbine efficiency is given by;

$$\eta_T = \eta_H \times \eta_V \times \eta_M$$  \hspace{1cm} (3)

Where, volumetric efficiency $\eta_V$ and mechanical efficiency $\eta_M$ are calculated from 1-D calculation based on JSME S-008-1999.

![Fig. 6 Computational domain for runner optimization](image)

3.2.2 Optimization condition

Total number of design variables is 27, which consist of parameters defining the blade camber line, meridian profile, inlet angle, outlet angle and so on. Evaluation points of objective and constraint function are shown in Fig. 7. The CFD calculations were carried out at 16 operating points to cover the whole operating range, and evaluated values were interpolated from those results. Turbine efficiencies at design point, over load operating point and part load operating point are chosen as objective functions. In addition, the minimum pressure coefficient $C_p$ on the suction surface of each inlet and outlet side is set as constraint function to prevent the occurrence of cavitation. $C_p$ is defined as follows:

$$C_p = \frac{(H_b - H_d)}{H}$$  \hspace{1cm} (4)

Where, $H_b$: Blade surface pressure head

$H_d$: Reference pressure head at runner outlet
Each limit value is determined same as the value of conventional runner result. Initial population number is 42, and those are selected from the primary optimization results performed at three evaluating points respectively. The number of generation is 25.

**Fig. 7** Evaluation points of objective and constraint function

### 3.2.3 Result

Fig. 8 shows the plot of objectives between the turbine efficiencies at design point and at over load operating point. Each axis value is normalized by the result of conventional runner. Where, the solution which has the highest turbine efficiency at design point among the solutions satisfying all constraint conditions is selected as the optimized runner. The optimized runner achieves significant improvement in efficiency at design point, but small improvement in efficiency at over load operating point.

Oil flow on the runner near the design point is shown in Fig. 9. The flow on optimized runner is smooth on the pressure surface of crown side while the flow on the conventional runner is sharply down in spanwise direction. Fig. 10 shows the streamline in draft tube near design point. From these figures, it seems that outlet flow of both conventional and optimized runner are almost not swirling. However, in conventional runner, the velocity magnitude near the crown side is slightly larger than that near the band side. In addition, the region of low velocity magnitude at outlet of draft tube in conventional runner is larger than the region in optimized runner. From the above mentioned differences, it is clear that the hydraulic loss of optimized runner is smaller near design point.
**Fig. 8** Plot of objectives between turbine efficiencies at design point and at over load operating point

(a) Conventional runner     (b) Optimized runner

**Fig. 9** Oil flow on runner near design point

(a) Conventional runner    (b) Optimized runner

**Fig. 10** Streamline in draft tube near design point

(a) Conventional runner    (b) Optimized runner
4. Conclusions

In the present paper, the new design optimization system by using PSO has been described. Applying the system to development for francis turbine, a single objective optimization for stay vane and multi objective optimization for runner were carried out. The obtained results are as follows:

1. Shape of stay vane defined by many design variables was optimized automatically by using the design system.
2. As a result of the runner optimization in wide operating range, it was possible to design a higher turbine efficiency runner with keeping cavitation performance.
3. It was confirmed that PSO was an effective algorithm for the design optimization of hydro turbine.

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