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Experimental study of redesigned draft tube of an Agnew microhydro turbine

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ABSTRACT

In this study, a surrogate-based optimization has been carried out for the components of an Agnew microhydro turbine. A neural network was constructed as the surrogate, while the Non-dominated Sorting Genetic Algorithm (NSGA-II) was used as the optimizer. The optimal design was found by numerical simulations, and the final design was manufactured and installed at the turbine outlet. The performance of the turbine components was then measured according to ASME performance test code. Comparison was carried out between the original draft tube and its modified under different operating conditions. The test results have confirmed that the pressure recovery factor of the new component increases by 20.3% and the loss coefficient diminishes by 4.0%, with regard to the original design under the best operating conditions.

1. Introduction

An Agnew turbine is a 45° inclined axial microhydro turbine whose blades can be adjusted to different angles. This type of turbine has been manufactured in different diameters (200, 300 and 500 mm) and installed at different sites in Scotland [1]. A scaled unit with a 150 mm tip diameter was manufactured at the Hydraulic Machines Laboratory (HML) of the Iranian Research Organization for Science and Technology (IROST) to investigate the applicability of the turbine for microhydro potentials in Iran [2].

Yassi [1] and Yassi et. al. [2] are the only researchers who has studied Agnew turbines, in which improvement of the turbine performance is investigated experimentally in design and part-load conditions. It is reported that installing guide vane mechanism improves the efficiency of the turbine as much as 23%, respected to the original design [2].

The draft tube in Agnew turbines is a diffuser, which connects the turbine outlet to the tailrace in order to recover the wasted kinetic energy at the runner outlet and convert it to a head rise and thus to increase the overall turbine efficiency. Since the Agnew turbine is a low-head axial type turbine operating at high rotation speeds, the performance of the draft tube has an important effect on turbine efficiency. The original draft tube of the turbine installed at the HML has been designed by simple traditional methods and by limiting the cone angle and the draft tube length.

The majority of literatures on this topic deal with the numerical investigation and experimental validation of flow phenomena occurring over the operating ranges of draft tubes and other components. In the last decade, the optimization of hydraulic turbine components has become more attractive to the researchers [3]. Lipej [4] used the Genetic Algorithm (GA) to perform a multi-objective geometry optimization of an axial flow hydro-turbine runner for various operating regimes. He found a region of low flow velocity behind the hub, in both the numerical and experimental approaches, which was minimized for the optimal design in order to reduce the energy loss in the draft tube. The optimal blade shape was determined by considering the chord-pitch ratio, the maximum profile thickness and the chamber position as the geometrical parameters, and the meridional velocity and the outlet vortex coefficient as the performance parameters. The efficiency of the final design was improved by 0.5% in the overload condition ($Q/Q_{opt} = 1.61$) and by up to 1.7% in the case of $Q/Q_{opt} = 0.39$.

Wu et al. [5] applied a CFD-based design optimization approach, in which the viscous 3D Navier-Stokes equations were solved by the STAR-CD in conjunction with the $k-\varepsilon$ turbulence model, to optimize the shape of the runner in a Francis turbine and its spiral casing. Comparison of the measured efficiencies of the old turbine

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Nomenclature

A	the area perpendicular to flow direction
AR	area ratio
ANN	artificial neural network
BC	boundary condition
ELC	energy loss coefficient
H	height above the tailrace
HML	hydraulic Machine Laboratory
I	turbulence intensity
K_u	circumferential blade speed ratio ($K_u = \frac{v}{\sqrt{2gL}}$)
L	head
M	modified case
N	rotational speed of turbine
$\mathbf{n}$	normal vector of the surface
O	original case
P	pressure
PRF	pressure recovery factor
Q	flow rate
R	dynamometer unloading
RMSE	root mean square error
SD	standard deviation
T	dynamometer loading
$\mathbf{u}$	velocity vector
v	circumferential velocity

Subscripts

in	inlet
max	maximum
out	outlet
tot	stagnation

Greek letters

α	angle of the draft tube
ρ	density
ϕ	flow coefficient

and the new design showed a peak efficiency of 95.3% for the optimized case, which was 3.3% higher than the original turbine efficiency. That efficiency peak was obtained at an approximate turbine power of 100 MW, about 23% higher than the existing runner power at the rated condition.

Madsen and Langthjem [6] optimized the wall shape of a two-dimensional incompressible diffuser to obtain its maximum pressure recovery factor (PRF). They used the response surface technique to estimate the objective function; and their derivative-based optimizer achieved a design with a higher area ratio (AR) than the ratio suggested in the literatures. They found that a convex-outward or bell-shaped design for the diffuser achieves a higher performance [7]; however, the response surface optimization produced a design which is mostly bell shaped with the end of the diffuser wall bent outward. The optimization results were the same for different CFD codes.

Marjavaara et al. [8] employed multiple surrogates in combination with the NSGA-II algorithm to optimize the shape of a simplified diffuser utilized in Francis turbines. They used five geometric design variables under two different operating conditions. Both the Response Surface (RS) methodology and Radial Basis Neural Network (RBNN) were considered to approximate the surrogate model. The analysis of the Pareto optimal solutions revealed that the fidelity of the RBNN is generally higher than the RS model. The predictive capabilities of the RBNN models were also better near the Pareto front; although the reliability of the quadratic models in this region was poor.

Shojaeefard et al. [9] showed that the swirl components of the inlet velocity vector are the most important performance parameters in the shape optimization of draft tubes. They found that the pressure recovery factor increases with the height and angle values over the design ranges.

The goal of present study is to optimize the shape of draft tube used in Agnew turbines. A surrogate-based optimization approach was implemented to redesign the shape of straight-divergent type of draft tube in an Agnew turbine. An artificial neural network (ANN) as a surrogate model is applied for optimization the design of draft tube and numerical simulations are performed to introduce the final design. The new design is then manufactured and installed at the outlet of the turbine in HML. The performance of the new draft tube is experimentally evaluated under various operating conditions.

2. System description

The schematic view of the turbine is presented in Fig. 1. As shown in the figure, Agnew turbine consists of four main parts: the casing, the runner and blade assembly, the housings, and the draft tube [2]. The turbine casing is flanged to the pipeline of the test rig, which has been designed in a way that changes the flow direction from horizontal to the direction of turbine's rotation axis. The turbine installed at the HML of the IROST has four rotating blades of 75 mm tip radius and 2.5 mm radial tip clearance. The housings consist of two bearings and sealing assembly. All the bearings are placed in the housings to restrain the radial and axial movements of the shaft. The sealing prevents water from leaking into the bearings. The draft tube is a simple straight pipe connected to the inlet of the casing. By reducing the kinetic energy loss at the outlet, the draft tube produces a negative head at the runner exit and improves the efficiency.

The design variables in the shape optimization problem of the draft tube are its height above the tailrace (H), and the cone angle (2α). Based on the physical constraints of the test rig, the lower and upper bounds for the height of the draft tube are 250 mm and 1500 mm, respectively. Besides this, the cone angle should be limited to less than 8°, according to the literature [10]. As the flow moves downstream and forms vortices and circulatory eddies, it detaches away from the wall and causes higher head losses at larger angles. For optimization purposes, the upper bound of the cone

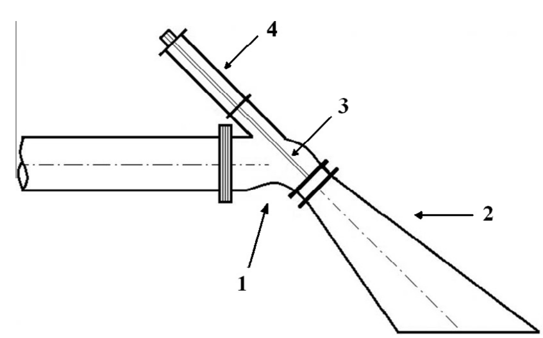

Fig. 1. Schematic view of Agnew turbine: (1) casing, (2) draft tube, (3) main shaft and (4) bearings housing.