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Multiple surrogate based optimization of a bidirectional impulse turbine for wave energy conversion

Rameez Badhurshah, Abdus Samad*

Department of Ocean Engineering, IIT Madras, Chennai 600036, India

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ABSTRACT

Oscillating water column based wave energy extracting system has a low efficiency due to the poor performance of its principal power extracting component, the bidirectional turbine. In the present work, flow over a bidirectional impulse turbine was simulated using CFD technique and optimized using multiple surrogates approach. The surrogates being problem dependent may produce unreliable results, if a wrong surrogate is selected. Hence, multiple surrogates such as response surface approximation, radial basis function, Kriging and weighted average surrogates were incorporated in this problem. Same design points were used to generate multiple optima via multiple surrogates to enhance the robustness of the optimization process. Numbers of guide vanes and rotor blades were chosen as the design variables, and the objective was to maximize the blade efficiency. Reynolds-averaged Navier–Stokes equations were solved for analyzing the flow physics. The computed results were used to train the surrogates and find the optimal points via hybrid genetic algorithm. The surrogates were further applied to find the optimal flow parameters by changing flow velocity and turbine speed. The relative efficiency enhancement through our present approach was about 16%. Detailed methodologies, analysis of the results and surrogate applicability have been presented in this paper.

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1. Introduction:

The depletion of fossil fuels and growing environmental issues has motivated to develop technology for the renewable energy systems [1]. One source of the renewable energy is the ocean wave, which is periodic in nature and having immense potential of producing energy [2]. Many methods like an oscillating water column (OWC), Archimedes wave swing, point absorber, overtopping device etc., have been deployed in the ocean, but the factors such as uncertainty of waves, extreme weather conditions, randomness of waves and tides etc., are the primary responsible factors for the lesser contribution towards technology development for power extraction from the sea or ocean [2,3].

Among the available devices, the most popular and extensively studied wave energy conversion device is OWC system [4]. The OWC system can be subdivided into fixed and floating structures. The fixed structures are installed near the shorelines while the floating structures are installed at offshore locations. The OWC is a partially submerged hollow cylindrical column consisting a bidirectional flow turbine or simply a bidirectional turbine installed inside the column [5].The alternating wave pattern produces a reciprocating air flow over the bidirectional turbine, thus rotating the turbine in a single direction.

During the primitive stages of extracting energy from the waves, the impulse turbines with flow rectification valves were employed. Because of the issues of maintenance and high energy losses involved with the valves, the valveless turbine was used as an alternative solution [6]. The popular bidirectional turbines are either reaction or impulse type. The reaction turbines operate on the principle of aerodynamics i.e., the pressure difference across the rotor helps to rotate the turbine. The impulse turbines operate on principle of rotodynamics i.e., the rotor rotates because of the impact of fluid jet on the rotor [7]. The reaction turbine inhibits the application because of its low operating range, high noise generation and poor starting characteristics [8,9].

The bidirectional impulse turbine has a symmetrical rotor sandwiched between two sets of guide vanes (GVs). The GVs essentially deflect the flow through the inlet and helps increasing the kinetic energy of flow. As a result, the fluid particles hit the rotor blade (RB) and gives 'impulse' to the turbine. The GVs are either fixed or pitch controlled type [6]. Although the pitch

* Corresponding author.
E-mail addresses: rameezib@gmail.com (R. Badhurshah), abdussamad77@gmail.com, samad@iitm.ac.in (A. Samad).

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controlled GVs show better performance, but they require high maintenance cost because of large number of moving elements. The impulse turbine has higher operating range and lower peak efficiency as compared to that of the reaction turbine [7].

The subject of optimization of turbines for an OWC has been overlooked and there is room for performance improvement via systematic optimization procedure. An optimization procedure involves experimental or numerical study and finding relationships among design variables and objectives, so that an optimal design or a set of optimal designs can be produced. While the experimental procedure involves high cost and difficulty, the computational or numerical procedure helps evaluating ample designs with limited cost. Coupling numerical simulation with optimization enables selection of optimum design with a limited time frame.

The earliest reported systematic optimization study was on reaction turbine airfoil blade shape modification for achieving multiple objectives [10]. Experimental works on impulse turbine show 0.7 hub to tip ratio-blade produces higher efficiency [7]. Over a wide range of flow coefficients, the optimal GV angle was 30°, and this angle produced the best efficiency [8]. The optimization of rotor blade section of an impulse turbine was carried by Gomes et al. [4]. They reported a two-step strategy comprising of camber line and thickness modification to maximize blade efficiency. Although many researchers and engineers are working on impulse turbine for OWC, there was no article or open document available to select number of rotor blade or GV and application of systematic optimization procedure via multi-fidelity analysis. Multi-fidelity analysis includes the optimization procedure coupling the higher accuracy model such as CFD and lower accuracy model such as surrogates.

The surrogates which are also called the surrogate models, surrogate approximation models, meta-models, low fidelity models or approximation models are being used for the engineering system optimization to reduce total design and optimization time [11,12]. The surrogates mimic the actual simulations of the high-fidelity models such as CFD or finite element etc., which involve huge computational time. The surrogate functions 'approximately' predict actual process or experimental process and the optimal points are predicted from these surrogates by an optimizer. The surrogates are dependent on the type of problem and selecting a single surrogate for a particular problem can lead to an erroneous prediction. Hence, multiple surrogates can produce better optimal designs without any extra computation cost of high fidelity simulation [13,14].

There are several basic surrogate models and those are reported in literature [13,15]. The surrogate models applied in the field of turbomachinery include response surface approximation (RSA), radial basis function (RBF), Kriging (KRG) and weighted-average-of-surrogates (WAS) models [15,16]. As the same CFD predicted data can be used to train all the surrogates, the costs of construction of the surrogates are low. Also, multiple surrogates increase the probability of finding best optima and the surrogates may produce an optimal zone in the design space. The surrogates increase the robustness of the optimal designs and may lead to sequential sampling based approach [10]. Alongside the design optimization, flow optimization ensures to find the optimum operating flow conditions for enhancement of the objective function.

The present work demonstrates the improvement of performance of an impulse turbine using surrogate modeling approach and CFD simulation. The work highlights the performance of different surrogates to apply to the renewable energy harvesting system applications and to find optimal numbers of RB and GV as well as optimum flow conditions which can enhance turbine performance significantly.

2. Problem description and numerical procedure

A bidirectional flow impulse turbine was chosen as the reference geometry [8] for this problem. The turbine and meshing the flow domain is shown in Fig. 1. The turbine has 30 rotor blade ($N_{rb} = 30$) mounted on the hub and 26 guide vanes ($N_{gv} = 26$) located on the either side of the rotor and mounted on the outer casing. The GVs guide the inlet flow to the rotor. The GVs may be fixed or self-pitching [17] and the fixed GVs were used in this work. The RB profile has a part of ellipse section on the suction side (SS)

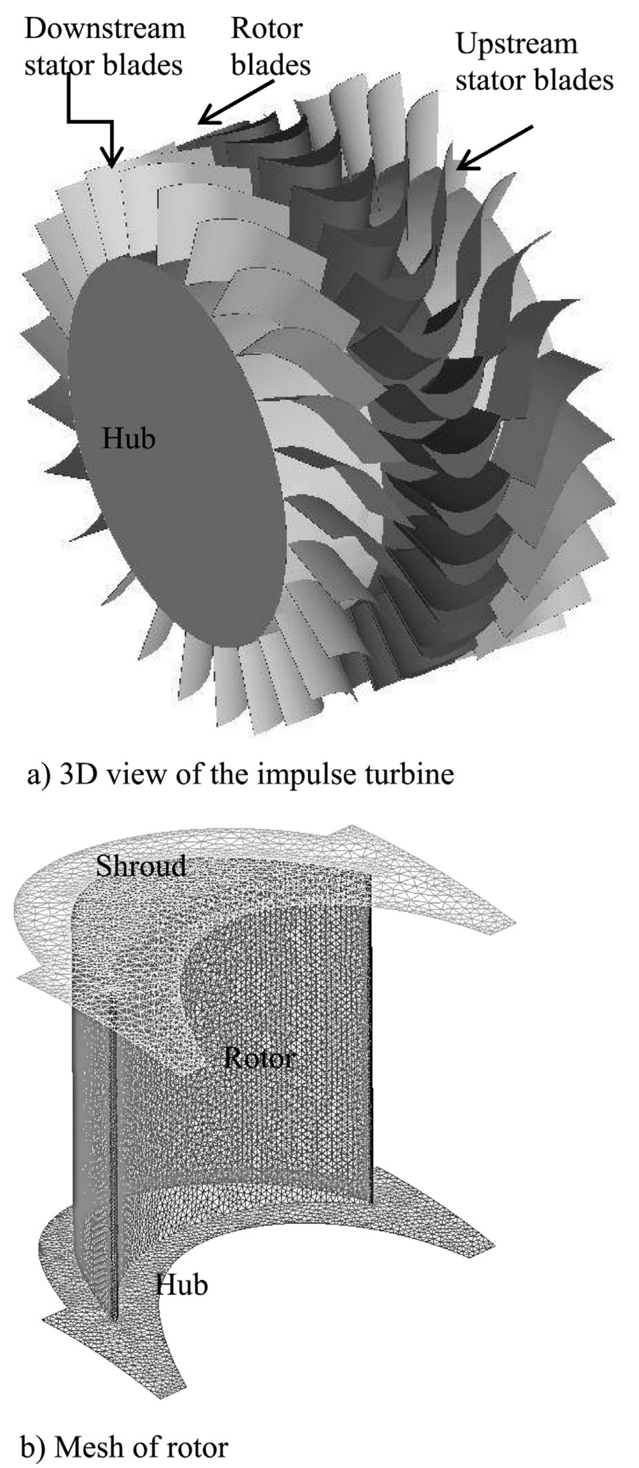

Fig. 1. Impulse turbine.

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