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Optimization of the cross section area on the meridian surface of the 1400-MW canned nuclear coolant pump based on a new medial axial transform design method ☆

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ABSTRACT

Canned coolant pump is the only rotating part of the nuclear island, which provides continuous power for the medium circulation. Therefore, new innovative approaches to improve the pump's performances are of great significance. To adjust the hub and shroud profiles spontaneously and control the scale of the design parameters effectively, a special investigation about optimizing the distribution of the cross section area on the meridian surface would be done here. In order to represent the meridian shape accurately with the corresponding expected cross section area distribution, the new design strategy established on the Media Axis Transform (MAT) design theory was presented firstly. Then with the integration of the new meridian design approach, Computational Fluid Dynamic (CFD) analysis, Central Composite Design (CCD), Respond Surface Method (RSM) and Non-nominated Sorting Genetic Algorithm-II (NSGA-II), an optimization system was ultimately established. Taking the scale model of CAP1400 (on a scale of 1:2.5) as the reference, the optimal cross section area distribution was gotten successfully after the optimization. Ultimately, the optimal distribution of the cross section area was obtained, and through CFD analysis and inner flow analysis, it can be found that the performances of the optimal sample are improved in relative to the reference model from $0.8Q_d$ to $1.2Q_d$. Most importantly, at the design point, the increasement of efficiency is 1.7%, while the head improvement is about 2.6%. The study here is expected to provide a new strategy for the meridian surface optimization of the large-scale turbomachinery with front and rear matching parts.

1. Introduction

The canned nuclear coolant pump is installed in the core location of the nuclear island, which can provide continuous power for the water circulation from the reactor to the steam generator (Zhu et al., 2017). The canned nuclear coolant pump has to work continually to supply energy for about sixty years without replacement. For the sake of the high radiation, the high power output and the long-term running characteristics in the working process (De et al., 2014; Nguyen and Namgung, 2017), the designed nuclear coolant pumps which could keep safe and stable properties are of vital importance. Additionally, with the advocation of green power nowadays, a canned nuclear coolant pump consuming low energy and having a good performance is still in great demand. Recently, based on the imported three generation coolant pump AP1000 abroad, China is trying to develop an advanced Pressurized Water Reactor (PWR) nuclear power unit CAP1400 which has a better ability to output power through a series of innovative technologies. Consequently, many innovative technologies have been proposed and applied in related studies (Lu et al., 2017a; Zhou and Wang, 2016). Research here would try to adopt a newly meridional shape design methodology to improve the pump performance.

As for the design approach to the pump impeller, the 3D (Three Dimensional) design method is much more preferred. Nevertheless, due to the complicated and the resource-consuming design process for the 3D design, another typical design mode reducing the dimensions and obtaining the 2D shape parameters is widely adopted (Yin and Wang, 2014). This kind of design mode is consist

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Nomenclature

Z_s, R_s, Z_h, R_h	The coordinates determining the meridian surface	$\eta_{0.8d}$	The efficiency at $0.8Q_d$ mass flow condition
z, r	The coordinates determining the medial axis	$\eta_{1.0d}$	Efficiency at $1.0Q_d$ mass flow condition
$\mathbf{p}$	The tangent vector on the medial axis	$\eta_{1.2d}$	Efficiency at $1.2Q_d$ mass flow condition
$\mathbf{q}$	The normal vector on the medial axis	$H_{1.0d}$	The head at design mass flow
$F(r_i)(i \in [1,5])$	Control points determining the cross section area	p_in	The total pressure at the inlet of the pump
$\hat{y}_i$	The output of RSM	p_out	The total pressure at the outlet of the pump
$\beta_0, \beta_i, \beta_{ik}, \beta_{ii}$	The coefficients of RSM	τ	The torque

of two aspects: one is the rotational blade design, and the other one is the meridian surface. The blade design and optimization are the main focus in previous studies (Zangeneh, 2010; Peng et al., 2002), but the specific researches about the meridian surface design are not so enough.

To get the ideal meridian surface in the previous studies, a popularized methodology can be briefly concluded as: with the simplified calculations and the expert experience, the meridional shape was drawn at first, and then through adjusting the discrete control parameters on the hub and shroud contours, the optimization algorithm was then applied to find out the optimal structures. For instance, Zhu et al. (2015) parameterized the hub and shroud contours with the Bezier curves firstly, and they used the Genetic Algorithm (GA) to find out the optimal parameters. Similarly, with the constraint of the arcs and lines on the hub and shroud contours, Pei et al. (2016) applied the Non-nominated Sorting Genetic Algorithm-II (NSGA-II) into the optimization of the meridian surface. Through remarkable achievements have been won previously, there are still some problems. Firstly, the hub and shroud contours are adjusted independently, which would easily lead to the non-synchronicity design problem or the excessive shape change. Moreover, due to the lack of the consideration of the physical constraints established on the aerodynamic characteristics, a great deal of design variables have to be settled in the optimization system, which would generate abundant samples. Therefore, a large scale of computing resources and time would be taken up before getting the optimal results with these traditional meridional design approaches.

To design the hub curve and shroud curve synchronously, the medial axis transform (MAT) theory firstly proposed by Choi et al. (1997) was adopted in Wang's study (Wang et al., 2011), and with the controlment of the medial axis, a new meridional design approach was proposed. Then with the application of the new design approach, Zhou et al. (2012) created a design system for the centrifugal pump after the investigation and statistical analysis of many typical structures. Continually, to explore the effect of the medial axis's shape, Wang et al. (2016) analyzed the flow characteristics of the fans with different medial axises. But actually, the medial axis and the distribution of the cross section area are the two key items. Apart from the effect of the medial axis, studies about the distribution of the cross section area are rare, thus, some further works need to be done to make up for the deficiency. Additionally, though with the synchronicity adjustment ability of the hub and shroud contours, the newly proposed meridian design approach based on MAT theory recently (Wang et al., 2011; Lu et al., 2017b) has not been adopted in any optimization works yet. However, since there still exists some minor errors between the target cross section area distribution and the final design result with Wang's (Wang et al., 2011) approach, some improved works need to be done to make the approach be appropriate for the meridional design process in the optimization system.

So, to do some innovative works and provide a new optimization strategy for the nuclear coolant pump, research here would try to adopt the improved meridian design approach to optimize the pump for performance improvement. Taking the scaled hydraulic model (on a scale of 1:2.5) of the coolant pump CAP1400 as the reference, the distribution of the cross section area in the impeller is investigated and optimized with the combination of a new meridional design approach and the Central Composite Design (CCD). The study here is mainly organized as follows: Part 2 illustrates the details of the new meridional shape design approach; Part 3 gives the information about the reference CAP1400, including the parameters of the structure, the simulating and experimental performance; Part 4 introduces the optimization methodology; Part 5 compares the flow characteristics between the optimal sample and the reference model. Part 6 provides the conclusions.

2. New strategy to adjust the cross section area on the meridian surface

To design the meridian surface with good flow characteristics, many physical constraints have already been proposed by previous studies (Wang et al., 2011; Zhou et al., 2012; Wang et al., 2016; Lu et al., 2017b). Accordingly, taking the partial effective constraints into consideration, research here would propose a new strategy to get the meridian surface with good flow characteristics through the controlment and adjustment of the cross section area.

2.1. Definition of the cross section area

In terms of a meridional channel with good performances, its hub and shroud contours should be tangent to a series of enveloping circles. To describe this phenomenon intuitively, the related constraint parameters are defined and shown in Fig. 1. In the figure, for a random enveloping circle in the channel, it has a corresponding cross section arc. After rotating the cross section arc around the axial axis, the revolutionary surface called the cross section area can be generated, which is marked in Fig. 1.

The calculation of the cross section $f(r)$ can be conducted with the following formula (Lu et al., 2017b):

$$f(r) = \frac{4}{9}\pi(r + R_h + R_s)\left\{\sqrt{[Z_s - z(r)]^2 + (R_s - r)^2} + \sqrt{(Z_s - Z_h)^2 + (R_s - R_h)^2}\right\} \tag{1}$$

where Z_s, R_s, Z_h, R_h are the coordinates of $\mathbf{S}, \mathbf{H}$ determining the meridional contours; z, r denote the coordinates on the medial axis of the meridian surface.

2.2. The other constraints to settle down the meridian surface

Enveloping formula The enveloping formula is an important part of the Medial Axis Transform (MAT) theory, which is firstly proposed by Choi et al. (1997). Since the design points $\mathbf{S}, \mathbf{H}$ determining the meridian surface are all located on the enveloping circle, the corresponding coordinates should also satisfy the