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# A symmetrical-nonuniform angular repartition strategy for the vane blades to improve the energy conversion ability of the coolant pump in the pressurized water reactor☆

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ABSTRACT

To increase the exterior characteristics and decrease the pressure fluctuations of the coolant pump synchronously, a symmetrical-nonuniform angular repartition strategy for the vane blades was herein proposed. Firstly, for the purpose of the effective parameterization of the vane, a new parameterized method considering the blade distances and the vane install location was defined and imported. Continually, based on the parameterized method, samples in the design space were generated with the Latin Hypercube Sampling (LHS) method. Then, with the integration of the generated database, Computational Fluid Dynamic (CFD) analysis, BP_Adaboost strong classifier, an optimization strategy was finally established. Taking the scale model of CAP1400 (on a scale of 1:2.5) as the reference, the symmetrical-nonuniform angular repartition strategy was applied in the practical design process, and 3 optimal samples were gotten at last. Through comparative analysis, it could be found that the new design structures have a better energy conversion ability, and the specific descriptions are as: the optimized vanes could make the coolant pump have a better exterior performance from $0.8Q_d$ to $1.2Q_d$ mass flow; most importantly, the unsteady analysis quantitatively demonstrated that the optimal structures could effectively decrease the pressure fluctuations, especially at the outlet of the coolant pump. The symmetrical-nonuniform angular repartition strategy for the vane blades is expected to provide a technical reference for the third-generation nuclear power plant design.

## 1. Introduction

China is trying to develop the advanced third-generation nuclear power plant, and remarkable achievements have been won recently (Long et al., 2017). Unfortunately, as the unique rotating components in the nuclear island, the coolant pump is the only product that cannot be designed and manufactured domestically. To make a breakthrough, the Chinese government has set up the national research program to encourage the colleges, the research institutes and the enterprise to do some theoretical and technological innovations. Focus on the theme about designing the advanced coolant pump, the previous studies have done relevant works, and the designed hydraulic model could satisfy the basic power output demand according to the primary model test (Zhou and Wang, 2016; Liu et al., 2018). However, according to the 2017 annual meeting of the Chinese National Basic Research Program in Xi'an, it is reported that the overlarge pressure pulsation problem still needs to be further solved after analyzing the experimental data of the first-stage prototype experiment. Accordingly, some innovative designs to improve the pump performance and decrease the pressure pulsation are of great significance. Hence, the study here would try to design a new vane structure to meet this practical demand.

As early as the 1960s, Lowson (1966) proposed the non-uniform blade distribution schema in the axial compressor, which could effectively decrease the pressure pulsation and improve the inner flows. And then, taking the axial fan as the study object, Ewald et al. (1971) adopted a new non-uniform manner to decrease the pulse and noise successfully. Taking the studies done by Lowson and Ewald as the reference, Li et al. (2014) proposed another kind of uneven guide blade in the coolant pump, it was known that the pressure pulsation could only be partially decreased, nevertheless, the pump performance can not be obviously improved. Apart from the non-uniform blade distribution structure, Jia et al. (2008) has done some investigations about the

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**Nomenclature**

| | |
|---|---|
| $Q_d$ | the design mass flow |
| $Q$ | the volume flow |
| $p\_in$ | the static pressure at the inlet of the pump |
| $p\_out$ | the static pressure at the outlet of the pump |
| $pt\_in$ | the total pressure at the inlet of the pump |
| $pt\_out$ | the total pressure at the outlet of the pump |
| $\tau$ | the torque |
| $S\_in$ | the pipe area at the inlet of the pump |
| $S\_out$ | the pipe area at the outlet of the pump |
| $\omega$ | the angular velocity of the impeller |
| $\rho$ | the density of the fluid medium |
| $\eta$ | the pump efficiency |
| $H$ | the torque |
| $X, Y, Z$ | the cartesian coordinate system |
| $F$ | the total axial thrust |
| $F_s$ | the axial thrust from the upper chamber |
| $F_i$ | the axial thrust from the impeller passage flow |
| $F_h$ | the axial thrust from the rear chamber |
| $\Delta t_i$ | the time step settled in the solver |
| $\theta_i$ | the angle controlling the blade distance |
| $m$ | the change degree to describe the blade distances |
| $\beta$ | the install angle of the vane |
| $d$ | the intermediate variable to determine $\theta_i$ |
| $N$ | the impeller blade number |
| $R^2$ | the goodness of fit |
| $l$ | the number of samples |
| $\xi$ | the node number in the input layer |
| $\psi$ | the node number in the output layer |
| $\zeta$ | the number of the hidden layer |
| $\sigma$ | the node number in the output layer |
| $\chi$ | the number of the bp neural networks |
| $g_j(x_i)$ | the predicting classify sequence |
| $e_t$ | the predicting error |
| $y_i$ | the expected classify sequence |
| $\alpha_j$ | the weight of the predicting sequence |
| $B_i$ | the normalization factor |
| $h(x)$ | the stronger classifier function |
| $\hat{Y}_i$ | the predicting results with the approximate model |
| $Y_i$ | the practical performances gotten from CFD |
| $\bar{Y}_i$ | the mean value of $Y_i$ |
| $\eta_d$ | efficiency at the design condition |
| $H_d$ | head at the design condition |
| $\theta_{1,\min}$ | the lower boundary of $\theta_1$ |
| $m_{\min}$ | the lower boundary of $m$ |
| $\beta_{\min}$ | the lower boundary of $\beta$ |
| $\theta_{1,\max}$ | the upper boundary of $\theta_1$ |
| $m_{\max}$ | the upper boundary of $m$ |
| $\beta_{\max}$ | the upper boundary of $\beta$ |
| $N_1$ | the number of nodes used to discrete $\theta_1$ |
| $N_2$ | the number of nodes used to discrete $m$ |
| $N_3$ | the number of nodes used to discrete $\beta$ |
| $TKE$ | the turbulence kinetic energy |
| $P$ | the static pressure |
| $t$ | the time |
| $amp$ | the amplitude |

install location between the rotor and stator in a low-speed axial compressor, and drew the conclusion that the appropriate install location could obviously improve the performance and decrease the pressure pulsation. Similarly to this work, Cheng et al. (2016) also did some research about the different install location of the vane in the coolant pump, and it was found out that the suitable circumferential position of the guide vane could effectively improve the pressure fluctuation.

So, it can be inferred from the previous studies that the non-uniform blade distribution and the changeable install location are profitable for improving the exterior characteristics or decreasing the pressure pulsation partially in most design cases. But does there exist a new structure which could improve the pump performance as well as the pressure pulsation synchronously? Also, the new structure with the non-uniform blade distribution and the new structure with the change of the install location were considered separately in previous studies, can these two structures be united together to make a breakthrough? Additionally, most of the previous studies just give the specific structure without the consideration of the search or optimization process, so that the random structure with a relative good performance instead of the most optimal structure may be given, therefore, the potential improvement could be ignored easily. And according to the other optimization works in the turbomachinery area (Zhu et al., 2015; Kim et al., 2017; Liu et al., 2017), the modern intelligent algorithm could be effectively adopted to find the optimal sample. Regarding of advancement of the intelligent algorithm, is it possible to be applied into the optimization process to find the optimal determined variables for the new structure proposed in this study?

Accordingly, in terms of the practical design demand and the questions mentioned above, the study here would propose a new vane fitting well with other components. Taking the scale model of CAP1400 (on a scale of 1:2.5) as the reference, the new structure would be adopted into the practical design process. The study here is mainly organized as follows: Part 2 illustrates the specific details about the reference hydraulic model of the coolant pump, including the working conditions, the experimental and simulating performance; Part 3 presents the symmetrical-nonuniform angular repartition approach and the parameterized control variables; Part 4 introduces the optimization methodology and its application to find the optimal structures; Part 5 analyzes the optimization results, and compares the unsteady characteristics between the reference and the optimal results. Part 6 provides the conclusions.

## 2. The reference model pump and the simulating approach

### 2.1. The reference pump

As mentioned previously, the scale model of the CAP1400 (on a scale of 1:2.5) is taken as the reference in this study. Presented in Fig. 1(a), four coolant pumps are installed in the nuclear island along with the hot leg pipe, the pressurizer, and the steam generator. And Fig. 1(b) gives the main hydraulic components of the coolant pump which are consisted of the front chamber, the mix-flow impeller, the vane and the case. Plus, there are six blades and fifteen blades in the impeller and the vane separately. Moreover, the twelve monitoring points in this study is marked with red in Fig. 1(b), whose coordinate information is listed in Table 1. The currently panned hydraulic model is designed to work at $Q_d = 384$ kg/s mass flow point with the 1485 r/min rotating speed.

### 2.2. Establishment of the test loop to evaluate the performances

To calibrate the simulation approach with Computational Fluid Dynamic (CFD) in Part 2.3, the high precision closed test loop was set up in the Chinese National Industrial Pump Test Center of the Shenyang Blower Works.

Fig. 2(a) shows the schema diagram of the test loop, and its main components are consisted of the Steady Pressure Jar, the Cavitation Suppression Jar, the Pressure Supply Pump, the Flow Regulating Valve