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Profile optimization of the impeller blade of a low-speed centrifugal pump using surrogate modeling

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Abstract. This article presents an alternative approach to optimizing the profile of the impeller blade of a centrifugal pump. The researches were carried out using modern methods of computational fluid dynamics and the ANSYS CFX software package. The target of optimization is to maximize hydraulic efficiency and head. The calculated variables were selected using the Bezier biquadratic curve, and calculation experiments were used to select reference points from the projected space. Particular attention is paid to the construction of a surrogate RSA model, which is used in numerical simulation. To study the optimal points, the NSGA-II genetic algorithm was used. In a process of processing the results, a standard response surface with a second-order polynomial was formed to predict integral parameters. It is concluded that the main problem associated with the optimization of design based on a surrogate model is the accuracy of modeling the approximation functions. Also, the use of several surrogates can increase the reliability of optimization with minimal computational costs.

Introduction

Centrifugal pumps are widely used in engineering and are used in almost all industries. The problem of increasing the efficiency of pumping equipment is relevant, since pumps consume a large amount of energy, so one of the main criteria when choosing a pump is its efficiency [1]–[9].

Today, hydrodynamic modeling methods are widely used as an effective tool to increase hydraulic efficiency in the design and optimization of flow parts of vane pumps. The main element of centrifugal pump optimization is the impeller. Changing its geometric parameters has the greatest impact on the performance of the entire pump. The flow phenomenon inside the impeller is complex. Most CFD-based impellers are trial and error, in which the design process is based on the experience of a design engineer [10]–[13]. However, in the design process, the use of numerical optimization methods makes it possible to perform a rational and systematic search in order to find a profile with improved performance.

To carry out optimization, surrogate models, also called surrogates, metamodels, or low-precision models, are very often used. The surrogate approximation function (approximation function) imitates a real phenomenon or high-precision model that is used for engineering analysis. High-precision model estimation, for example, the CFD method, requires longer computational time, while surrogates can be estimated hundreds of times faster in a limited period of time. It is important to understand that a universal surrogate that could be used to solve all problems does not exist. The main problem of

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surrogate modeling is the complexity of modeling high-precision simulations, i.e. surrogates depend on a specific problem, and one surrogate cannot be used to solve all problems, so designers need to choose a suitable surrogate that can give sufficient accuracy and will have a more reliable result.

To optimize the profile of the impeller blade, two objective functions were selected: hydraulic efficiency and pressure. Hydraulic efficiency (η) is given by formula:

$$F_1 = \eta = \frac{H}{H_m},$$

where H and H_t are the actual and theoretical pressure, respectively.

According to the Euler equation, the head (H) generated by the impeller blade is given by the formula:

$$F_2 = H = \frac{c_{u2}u_2 - c_{u1}u_1}{g},$$

where c_{u1} and c_{u2} are the input and output components of the peripheral speed; u1 and u2 are the peripheral speeds.

The algorithm of the optimization process based on surrogate modeling is presented in Figure 1. Initially, the task was formulated and a space for design was created. It is limited by the lower and upper limits of the variables. The next step is to build a surrogate and search for optimal points. Optimal points are determined using a genetic algorithm.

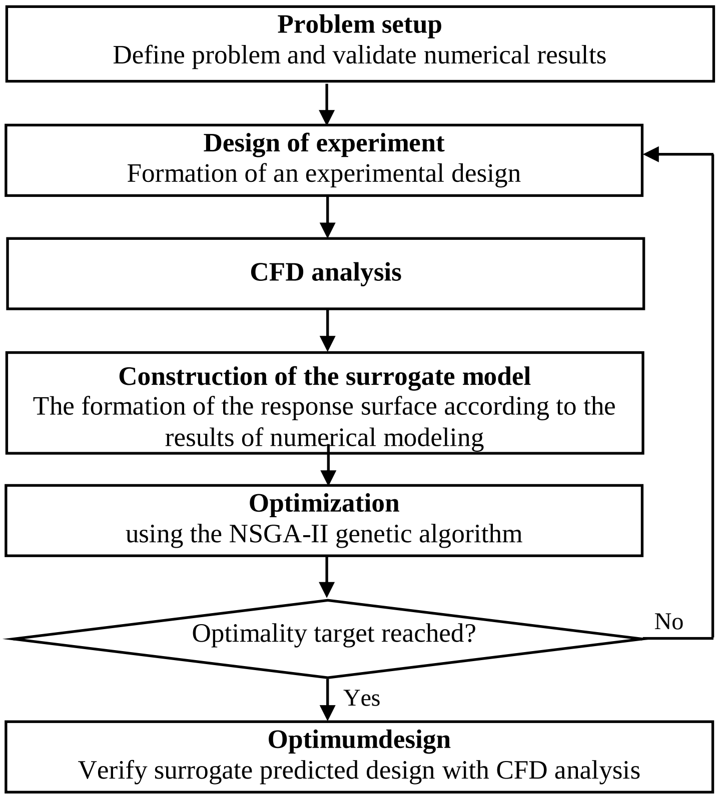

Figure 1. Flowchart of the optimization procedure

Genetic algorithms belong to the class of evolutionary algorithms. These algorithms search for the optimal solutions of various target functions, based on the principles inherent in the processes of natural evolution and the genetic mechanisms used in it. The use of genetic algorithms due to the nonlinearity of the target function is a reasonable choice.

Among the various modifications of genetic algorithms, the most common Non-Dominated Sorting Genetic Algorithm (NSGA-II), which was used in this work. Under the conditions, the value of the initial population was set to 1000, the subsequent ones received a similar restriction. Their maximum number was 20. The purpose of the genetic algorithm is to maximize hydraulic efficiency (η) and head (H).

The accuracy of the surrogate depends on the number and location of design points in the design space. Surrogates also depend on the task, which makes it difficult to choose any surrogate for a particular problem. In this work, the response surface approximation (RSA-model) was used.

The RSA model as a surrogate model is used to estimate the values of the target function. It is a technique of polynomial function selection for discrete responses obtained from numerical calculations. In this work, the second order polynomial is used as a response function:

$$F(x) = \psi_0 + \sum_{j=1}^{n} \psi_j x_j + \sum_{j=1}^{n} \psi_{jj} x_j^2 + \sum \sum_{j \neq j}^{n} \psi_{ij} x_i x_j ,$$

where n is the number of variables, x and ψ are the regression coefficients.

Real engineering problems are solved using one- or multi-criteria optimization methodologies, where the latter option is preferred [14]–[18]. Multi-objective optimization considers several conflicting criteria that are optimized simultaneously. This approach includes the search for a variety of Pareto optimal solutions and the construction of a relationship between the criteria, the combination of criteria, etc. The multi-objective problem can be solved by evaluating weight factors for each individual criterion, namely:

$$F_C = \sum w_i F_i ,$$

where i=1, 2, ... n, and n is the number of criteria.

Mathematical model

The ANSYS CFX computational fluid dynamics software module was used to conduct a numerical experiment.

The geometry of the impeller of the centrifugal pump is shown in Figure 2.

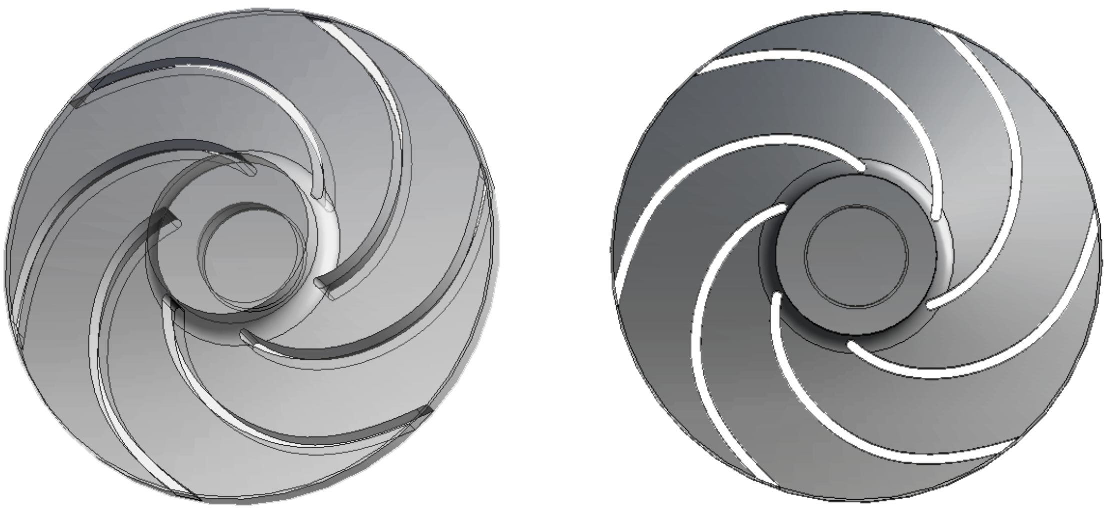

Figure 2. Impeller geometry

The main parameters of the calculation model are presented in table 1.

Table 1. Model parameters

Parameter	Description
Flow domain	Single impeller
Number of blades	6
Mass flow rate	25 m^3/h
Head	50 m
Rotation frequency	2950 rpm
Mesh model	Unstructured hexahedral
Number of elements	4,7 million
Fluid	Water, 20^oC
Turbulence model	k-ε
Inlet/Outlet	Inlet — mass flow rate, outlet — pressure

Initially, a parametric model of the impeller was created, in which the meridional section remained unchanged, and the profile of the midline of the blade was determined using parametric dependencies. To define the midline profile, we used the Bezier curve with five control points, shown in Figure 3. Such a function can be fully defined by nine parameters: the angles φ1, φ2, φ3, φ4 and the radiuses r_{in}, r_1, r_2, r_3, r_{out}. It was also decided to reduce the number of variables to 4 — φ1, φ2, φ3 and φ4 to reduce the size of the search space. During the optimization search, the radiuses r_{in}, r_1, r_2, r_3, and r_{out} were constants.

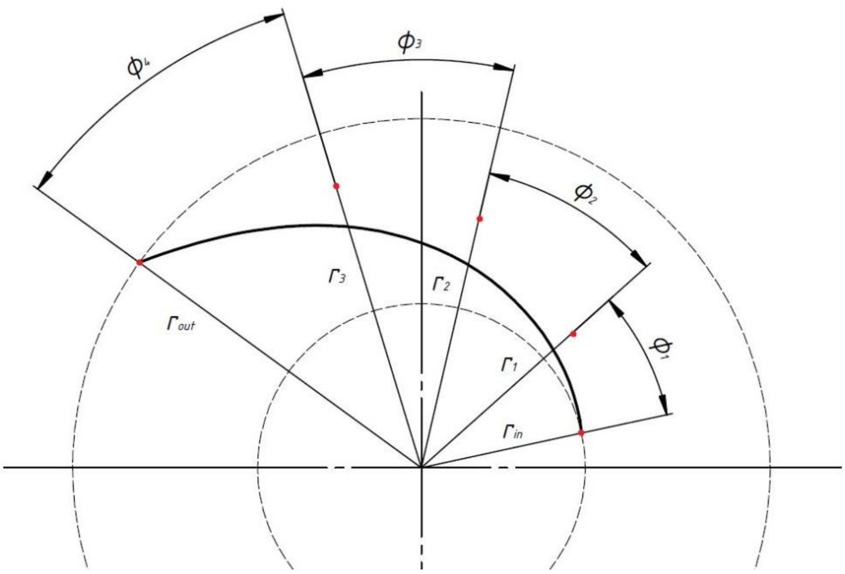

Figure 3. The profile of the blade profile

The angles φ1, φ2, φ3, φ4 were chosen as the calculated variables for constructing the profile of the middle line of the blade. The ranges of variables shown in the table 2, were selected based on preliminary calculations and search.

Various researchers have carried out a lot of work, which considered all kinds of surrogate models, as well as performed a comparative analysis [19] - [20]. In further optimization, one of the varieties of surrogate models, highly dependent on the response received from high-precision models, was used to obtain functional dependencies of the criteria change. It is important to choose the best option, otherwise you can get erroneous results. We used the response surface approximation (RSA-model).

Table 2. Variable Ranges

Parameter	Range of parameter values, deg
φ_1	20 … 40
φ_2	20 … 35
φ_3	15 … 35
φ_4	5 … 20

Figure 4 shows the response surfaces obtained using the RSA model, based on the results of numerical simulation according to the experimental plan of 25 points.

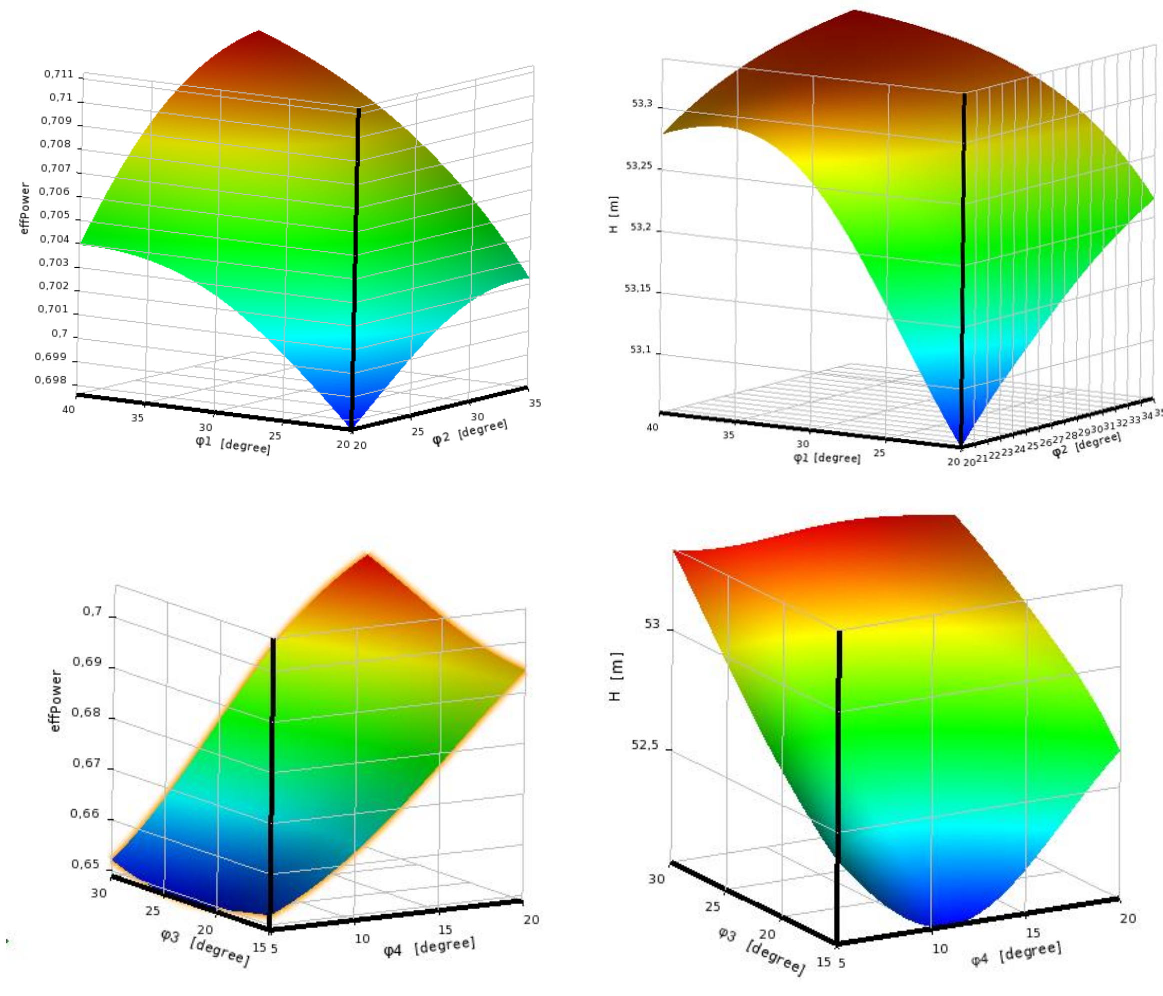

Figure 4. Response surfaces

For this type of surrogate model, a set of Pareto optimal solutions were obtained, from which three optimal points were selected for subsequent verification by numerical simulation. The results are presented in table 3.

Of these three points, one with the highest head and efficiency values was selected for verification.

The results of the calculation of the optimized impeller are presented in table 4.

Table 3. Relative deviations of simulation results

№	Deviation from the predicted value		Deviation of the optimized version from the original	
	H, %	η, %	H, %	η, %
1	1,86	0,22	1,37	6,15
2	1,73	0,19	1,43	6,23
3	1,40	0,03	1,57	6,57

Table 4.Optimization result

Geometry	Variableparameter				Predictedvalue	
	φ_1	φ_2	φ_3	φ_4	H, m	η, %
Original	26,7	30,82	17,55	9,83	52,18	65,86
Optimized	25,4	28,74	34,86	20	53,77	70,47

Conclusion
This article successfully evaluated the design capabilities of a surrogate RSA model. As an example, the impeller of a low-speed centrifugal pump was selected. When optimizing the profile of the midline of the blade, the increase in hydraulic efficiency and pressure amounted to 4.61% with a simultaneous increase in pressure by 1.59 m compared to the initial form. The increase in efficiency occurs due to the reduction of flow losses. Since surrogates do not work well in all cases, it is suggested that they be reused in the calculations. These optimization results indicate the effectiveness of this technique.

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