Full 3-D viscous optimization design of a reversible pump turbine runner

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Abstract. The bi-directional operation of reversible pump turbines presents a great challenge in terms of runner design. In the present paper, an optimal design system for the pump turbine runner is presented by coupling three-dimensional (3-D) inverse design with the Computational Fluid Dynamics (CFD), Design of Experiment (DoE), Response Surface Methodology (RSM) and Multi Objective Genetic Algorithm (MOGA). A pump-turbine runner was designed using the system, with selecting blade loading distributions and blade lean as the input parameters, and the runner efficiency for both pump and turbine mode as optimization objectives. The CFD results show that a high efficiency runner can be designed using the present system.

1. Introduction
Reversible pump-turbines are widely used in pumped storage plant nowadays. As a key component of a pump-turbine, the runner is needed to rotate in two directions, operated as a turbine or a pump. This brings a great challenge for the design of pump-turbine runners, since the characteristics of the runners are different in the pump and turbine.

Practically, the shape of the pump-turbine runner is close to the impeller shape of centrifugal pumps. Therefore, the pump turbine runners are usually designed based on the pump mode, and then checked and verified with the turbine mode. Therefore trial and error in numerical analyses and model tests is necessary and experiences of the designers are indispensable.

In this paper, optimization design system is suggested for the design of pump turbine runners by coupling 3-D inverse design method, computational fluid dynamics (CFD), design of experiment (DoE), response surface methodology (RSM) and multi objectives genetic algorithm (MOGA). Firstly, a brief description of the system is given. Then, optimization system is applied to a pump turbine runner. The optimization results of the runner are shown. Comparisons and analyses of design parameters are also conducted in order to offer a guideline for the design of pump-turbine runner.

2. Description of the optimization design system
2.1. Three-dimensional inverse design
Although direct and inverse iterative design method is proposed by the authors [1], in order to make the system more applicable, the commercial software TURBODesign is used to parametrically decide
the blade geometry. TURBODesign is developed based on a three-dimensional inviscid inverse design method proposed by Zangeneh [2].

The inputs required by TURBODesign5.1 are as follows: (i) design specification and design conditions, (ii) meridional geometry, (iii) blade thickness, (iv) blockage factor, (v) blade loading, (vi) blade stacking. Among these inputs, the blade loading and blade stacking are main parameters, which determine the blade’s shape [3,4]. The blade stacking specifies the blade lean at the trailing edge in the pump mode, which affects the wrap angle of the blade [5,6].

The blade loading specifies distribution of \( \frac{\partial (r\overline{V_\theta})}{\partial m} \), which is the derivative of circumferentially averaged velocity momentum \( r\overline{V_\theta} \) along the meridional distance. For incompressible potential flows, \( \frac{\partial (r\overline{V_\theta})}{\partial m} \) is directly connected with the pressure difference across the blade

\[
p^+ - p^- = \frac{2\pi}{B} \rho \overline{W_{end}} \frac{\partial (r\overline{V_\theta})}{\partial m} \quad (1)
\]

where \( B \) is the number of blades and \( \overline{W_{end}} \) is the meridional velocity on the blade. Therefore, the pressure distribution for the blade can be easily controlled by manipulating \( \frac{\partial (r\overline{V_\theta})}{\partial m} \).

2.2. CFD analysis

The CFD analyses are used to obtain the runner performances both in pump mode and in turbine mode. In this paper, the widely used software ANSYS CFX is used and full flow passage including spiral casing, stay and guide vanes, runner and draft tube is calculated in order to obtain more accurate results.

2.3. Optimization strategy

Figure1 shows the flow chart of the optimization process. As the blade geometry is provided by 3-D inverse design and the performance parameters are given by CFD evaluations, RSM coupled with DoE is used to build the approximate functions correlating the performance parameters to the design parameters. Then MOGA is applied to search the optimal geometry. The commercial optimization software iSIGHT is used in this paper, which can provide the means of DoE, RSM, and MOGA.

![Figure 1. Procedure for multi objectives optimization](image-url)
The calculation of the optimization process in Fig.1 is very fast since the objective functions are
given basing the RSM model and no further CFD calculations are required. As a result, the Pareto
front of the optimal solutions is obtained. On the Pareto front, the best selections with different
performance parameters can be chosen based on the design specifications.

3. Optimization design of a pump turbine runner

3.1. Design specifications
The runner under consideration is a middle high head pump turbine. For turbine mode, the rated head
is \( H_r = 259.0 \text{m} \), the rotation speed is \( n_r = 300 \text{rpm} \), the output power is \( P_r = 255.1 \text{MW} \). The maximum and
the minimum heads for pump mode are \( H_{\text{max}} = 298.0 \text{m} \) and \( H_{\text{min}} = 239.0 \text{m} \) respectively, the flow
discharge should be assured to be bigger than \( 70.0 \text{m}^3/\text{s} \), and the maximum input power should be less
than 270MW at \( H_{\text{min}} = 239.0 \text{m} \).

In order to carry out measuremental investigation in a test rig satisfying the IEC standard in the
following time, the runner model was designed. A sketch of the runner is shown in Fig.2, while the
main design specification and geometrical parameters are listed in Table 1.

| Table 1. Design specifications and geometrical parameters |
|---------------------------------------------------------|
| Design specifications                                    |
| Rated head in pump mode \( H_r \)                        | 34.79 m |
| Rated discharge in pump mode \( Q_r \)                  | 336.89 l/s |
| Rotational speed \( N_r \)                              | 1200 rpm |
| Geometrical parameters                                  |
| Diameter in high-pressure side \( D_h \)                | 448.20 mm |
| Width in high-pressure side \( b_2 \)                   | 51.16 mm |
| Hub diameter in low-pressure side \( D_{lh} \)           | 143.50 mm |
| Shroud diameter in low-pressure side \( D_{ls} \)        | 270.00 mm |
| Blade number \( B \)                                    | 7 |

3.2. Optimization design
The main goal of this paper is to confirm the applicability of the optimization design system described
in section 2 in the design of the pump turbine runner. As the first application of the system in the
optimization design of the pump-turbine runner, runner’s efficiencies for the pump design point and
turbine’s rated point were chosen as the optimization objectives and the pump head was set as a constraint. Blade loading and blade lean were selected as the optimization parameters.

The blade loading was controlled by specifying the distribution of \( \frac{\partial(r\overrightarrow{V}_\theta)}{\partial m} \) on the hub and shroud. As shown in Fig.3, four parameters are necessary to define the blade loading, including intersection points NC and ND, slope of middle linear line SLOPE, and the blade loading at leading edge for pump blade DRVT. Therefore, a total of eight parameters were used for the control of the blade loading. A linear blade lean was also imposed at the trailing edge of the blade at pump mode.

In order to create the database, 40 runner configurations were generated in DoE. For each configuration to be analysed, CFD calculations were carried out in order to obtain the efficiencies. Three-dimensional full passage, as shown in Fig.4 is built in order to calculate the runner efficiencies precisely under different operation modes.

Hexahedral meshes were adopted in full passages except spiral casing tongue domain for its complicated structure. Total mesh number was about \( 3.5 \times 10^6 \), including \( 9 \times 10^5 \) for the runner. RNG \( k - \varepsilon \) turbulence model was used in the calculations.

### Table 2. Comparison of the optimization and baseline design efficiency

| Case | mode       | Efficiency \( \eta \) (%) | RSM | CFD |
|------|------------|---------------------|-----|-----|
| B1   | Pump       | 93.67               | 95.54 |
|      | Turbine    | 97.68               | 95.10 |
| B2   | Pump       | 95.07               | 95.55 |
|      | Turbine    | 96.20               | 95.12 |
| B3   | Pump       | 95.67               | 95.56 |
|      | Turbine    | 95.52               | 95.09 |
| B4   | Pump       | 96.49               | 95.62 |
|      | Turbine    | 94.50               | 95.00 |
| Base design | Pump | —                  | 95.40 |
|      | Turbine    | —                  | 93.11 |

3.3. Optimization results and analysis

The Pareto front obtained from the calculations is shown in Fig.5. There are about 10,000 different runners. For each runner, its design parameters are decided by MOGA and performances are estimated by RSM. It is obvious that the runner efficiency is a trade-off between the pump mode and turbine mode.
The comparison of the efficiencies of four optimized runners at the Pareto front in Fig.5 and the initial baseline runner is reported in Table 2. The CFD results given in Table 2 were obtained from the redesigned runners using the optimized blade loading and blade lean. According to Table 2, the runner’s efficiency in turbine mode can be increased by about 2%, while efficiency in pump mode remaining almost unchanged.

The blade loading distribution for the optimized runner and the initial runner is shown in Fig.6, while Fig.7 gives the shape of initial runner and an optimized runner. According to Fig.6 and Fig.7, it can be found that fore-loaded distribution at both the hub and shroud, coupled with a blade lean contribute to improve efficiency of the runner in turbine mode.

Figure 6. Comparison of blade loading between baseline and optimized design (B2)

Figure 7. Comparison of runner shape

Figure.8 shows the effects of the main design parameters on the runner efficiencies. The graphs were obtained by searching effects of one parameter on runner efficiency while keep other parameters to the default. From the graphs, it is easy to find that each parameter has adverse effects on runner efficiencies for pump mode and turbine mode, which means the complexity in designing a pump turbine runner with high efficiency at both two operation modes.
4. Conclusions

The paper presents an optimization design system for the pump turbine runner, which consists of 3D inverse design, CFD, DoE, RSM and MOGA. DoE and RSM technique can reduce the computational cost substantially and expand the optimization space greatly, MOGA makes optimization process completely automatic, while several objectives can be optimized simultaneously.

A middle-high head pump-turbine runner was designed by using the proposed system. With the optimization of blade loading distribution and blade lean, the runner efficiency can be increased about 2% at the turbine mode while the efficiency at pump mode remains almost unchanged. Efficiency for both pump and turbine modes can reach over 95%.

References

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