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An adjoint-based optimization method for reducing the axial force of a reactor coolant pump

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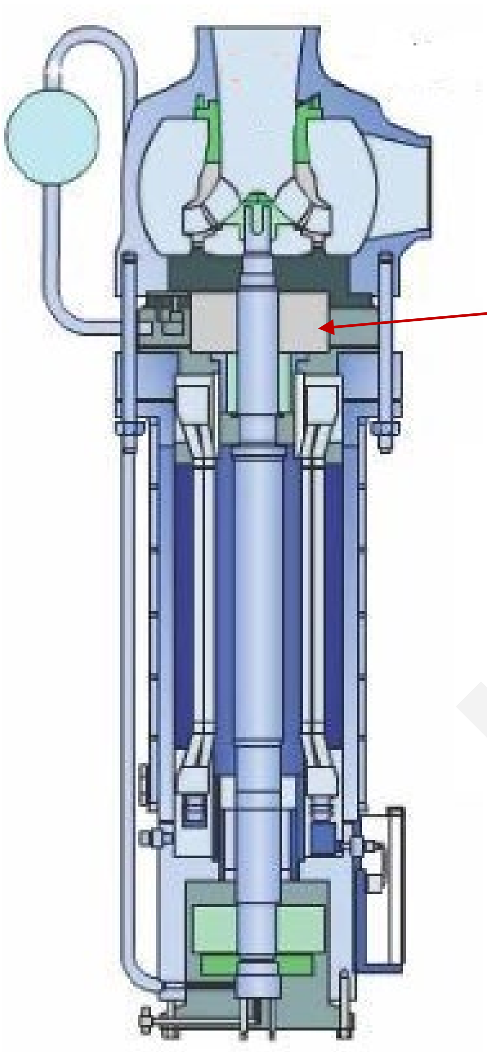
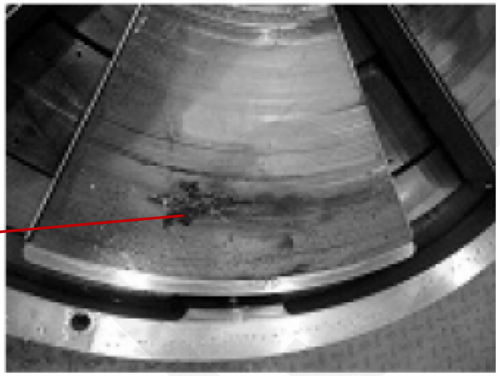
Axial load accident of shielded RCP



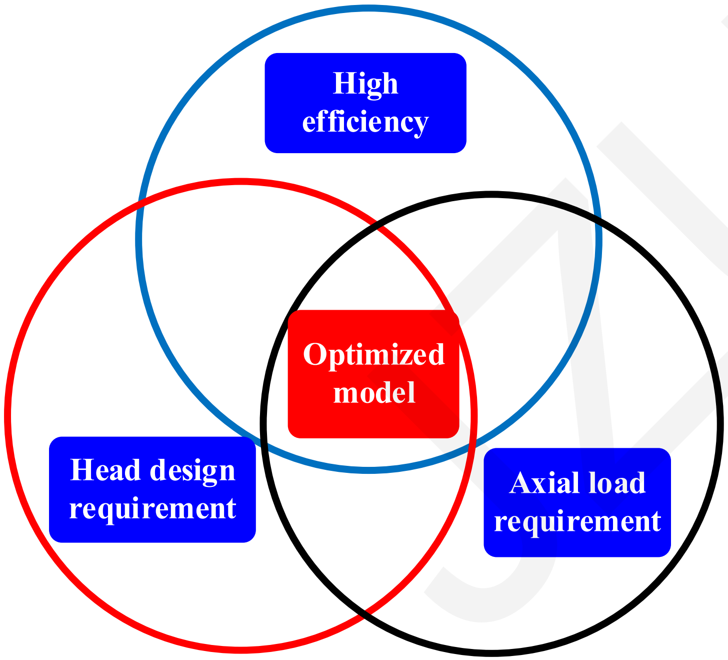


Bearing wear

On September 12, 2009, in the AP1000 reactor coolant pump (RCP) type test, the thrust bearing balance plate components were excessively worn, linear cracks appeared on the hard surface the thrust disc, and wear particles appeared on the worn parts.

Optimization of axial force and efficiency of RCP

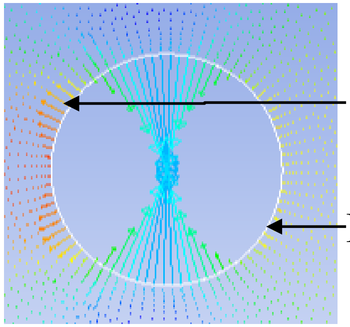
- Optimizing the 3D shape of the blade can reduce the axial force
- The shape of the blade has an important influence on the head and efficiency



Simultaneous optimization of axial force and hydraulic efficiency of RCP under restricted head conditions

Multi-objective gradient calculation

Determining the synchronization optimization scheme by the gradient optimization method



$$\frac{d\text{Optimization target}}{d\text{Structural shape}}$$

Fluid domain boundary

Adjoint operator	$\lambda^T = -\mathrm{d}_x f * \mathrm{d}_x g^{-1}$
Gradient of Optimization target	$\mathrm{d}_p f = \lambda^T \mathrm{d}_p g$

The adjoint method is the “diagnostic” of hydraulic performance

Multi-objective weighted combination

Head function $J_{\mathrm{H}} = \frac{(H - H_{\mathrm{T}})^2}{0.01 H_{\mathrm{T}}^2}.$

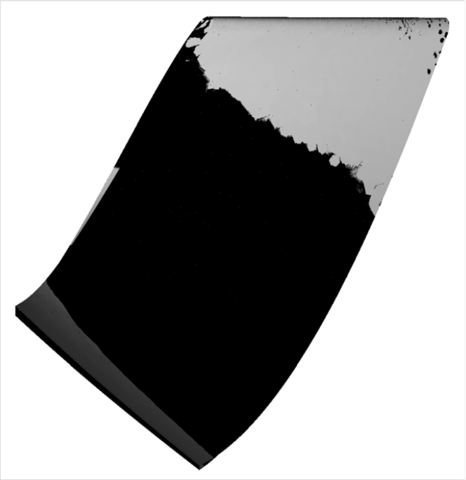
Axial force function $J_{\eta} = -\frac{\eta - \eta_0}{\eta_0}.$

Efficiency function $J_{\mathrm{Fa}} = \frac{F_{\mathrm{a}} - F_{\mathrm{a0}}}{F_{\mathrm{a0}}}.$

$$J_{\mathrm{m}} = k_1 J_{\mathrm{H}} + k_2 J_{\eta} + k_3 J_{\mathrm{Fa}}.$$

Influence of blade shape on different performance

- Blade deformation trends corresponding to different objective functions



Deformation trend of the head function

Deformation trend of the efficiency function

Deformation trend of the axial force function

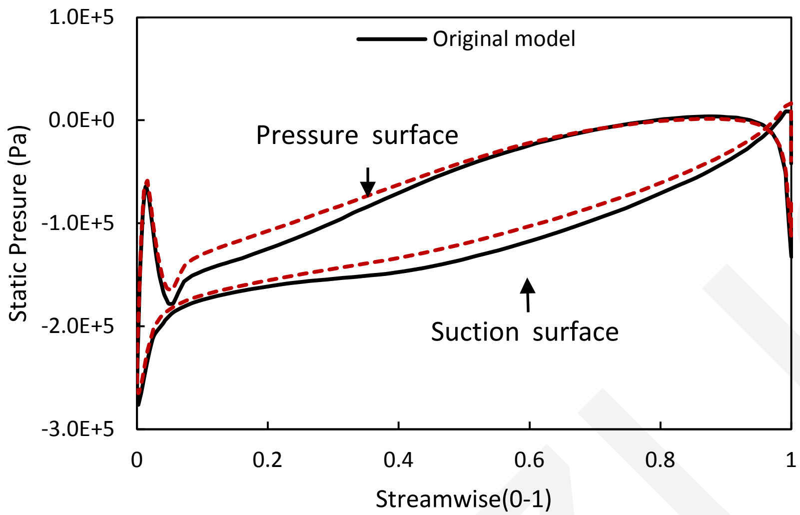
Deformation trend of the multi-objective function

The dark color indicates that the areas deforming along the normal outward direction increase the objective function, and the opposite is indicated by the light color

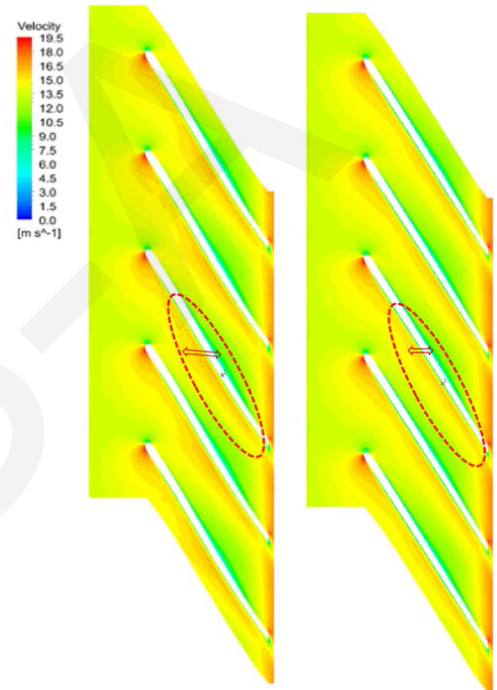
- The multi-objective function gradient value is the weight of each single-objective gradient value.
- Due to the constraints on the impeller head, the area to be optimized is mainly distributed at the lower half of the blade near the outlet edge.

Optimization results of the impeller

Optimization of axial force efficiency of impeller under head restraint



Improvement on pressure distribution



Improvement on flow separation

- Improving the hydraulic axial force and efficiency of while keeping the hydraulic head at a constant value

	Efficiency	Axial force	Head
Initial	93.376%	984.166 N	21.756 m
Optimized	96.571% ↑	946.986 N ↓	21.752 m

Conclusions

- 1. Compared with traditional stochastic algorithms, this method avoids the use of a large number of sample points to find the optimal path and can directly iterate along the gradient direction to optimize the model.
- 2. The optimization method combines the adjoint solution with the RBF-based mesh deformation, so the flow calculation and structural deformation are executed automatically, which ensures smooth and efficient updating of the flow field mesh.
- 3. After optimization, the axial force and hydraulic efficiency of the impeller are improved. The obtained results validate the feasibility of the adjoint method in the optimization design of centrifugal pumps.
- 4. Based on the results from this study, this method can also be extended to optimize the performance of other hydraulic loads, such as pressure fluctuation.