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Aerodynamic optimization for low pressure turbine exhaust hood using Kriging surrogate model☆

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ABSTRACT

To further improve the pressure recovery capability of low pressure turbine exhaust hood, an aerodynamic optimization system has been developed on the Matlab platform. The shape optimization for a scale model of a low pressure exhaust hood is numerically performed to maximize the mass averaged pressure recovery coefficient while subjecting to geometric constraints. Two cubic Bezier curves are used to represent the flow guide and the bearing cone profiles, respectively. Evaluation of the aerodynamic performance of the model is carried out by the commercial CFD simulator CFX. The Kriging model is used as a surrogate, which establishes a global mapping between design variables and objective function. In order to seek a balance between local and global search, an adaptive sample criterion is employed. The optimal design exhibits a reasonable performance improvement compared with the original design.

1. Introduction

The low pressure exhaust hood of a condensing steam turbine is used to connect the last stage turbine and the condenser. It recovers the turbine leaving kinetic energy into potential energy. This pressure recovery allows the turbine exhaust pressure lower than the condenser pressure, thus increasing the turbine work. Tindell et al. [1] found that approximately 15–20% pressure recovery capability was lost in the exhaust hood. It is therefore clear that the low pressure exhaust hood is a component that has the potential to be improved considerably in terms of aerodynamic efficiency. Most previous studies of exhaust hoods have been carried out by experimental and numerical approaches, as demonstrated by Liu et al. [2], Zhang et al. [3], and Sultanian et al. [4]. These studies help us understand the complex three-dimensional flow characteristics in exhaust hoods. However, the primary concern in the industry is to improve the overall performance of exhaust hoods instead of to analyze and understand the flow structure. A number of experimental and analytical attempts have been made to improve turbine exhaust system performance. Lu et al. [5] tested gas turbine exhaust volute to select optimum geometric parameters. From the analysis of experimental data, they proposed a design criterion for exhaust volutes. Mao et al. [6] used an experimental design technique to conduct limited model tests to get an optimized axial turbine exhaust hood configuration. Their design process was guided by repeating trial experiments, which required a great deal of time and costs. In recent years, optimization based on flow analysis is becoming increasingly popular in the field of engineering design. In some cases, evolutionary algorithms are used to ensure reaching the global optimum. However, the high computational costs associated with evaluating a large number of objective functions prevent applications of evolutionary algorithms to practical engineering design problems. In order to cut the prohibitive costs, a low fidelity surrogate model can be used to reduce the number of required objective function evaluations. Queipo et al. [7] and Simpson et al. [8] reviewed various surrogate models used in engineering design. Madsen et al. [9] demonstrated the utility of response surface model in a diffuser design. Marjavaara et al. [10] optimized the shape of a simplified hydraulic turbine diffuser using response surface and radial basis neural network based optimization strategy in conjunction with an evolutionary algorithm.

In the present work, an aerodynamic optimization system has been developed on the MATLAB platform. The system has four components: the geometry parameterization modelling module, the structured mesh generator ICEM-CFD, the aerodynamic simulator CFX, and the Kriging surrogate based optimizer. The shape optimization for a scale model of a low pressure exhaust hood is numerically performed to maximize the mass averaged pressure recovery coefficient while subjecting to geometrical constraints. Results show that the aerodynamic performance of the exhaust hood model can be improved.

2. Geometry parameterization and optimization problem definition

The exhaust hood model consists of an upstream extension section, an axial–radial diffuser, and an exhaust volute. The

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Nomenclature

B	Bernstein basis function
n_s	number of sampling points
n_{dv}	number of design variables
p	static pressure
p_0	total pressure
P	coordinates of Bezier curve control point
$\mathbf{r}(\mathbf{x})$	correlation vector
$\mathbf{R}$	correlation matrix of Kriging
$R(\mathbf{x}^i,\mathbf{x}^j)$	correlation function between $\mathbf{x}^i$ and $\mathbf{x}^j$
$s^2(\mathbf{x})$	mean squared error of prediction
x,y	Cartesian coordinates
$\hat{y}(\mathbf{x})$	generalized least square estimator of $y(\mathbf{x})$
$z(\mathbf{x})$	departure of Kriging
Greek symbols	
ξ	local coordinate
η	local coordinate
λ	optimum design vector
μ	constant trend of ordinary Kriging
$\hat{\mu}$	maximum likelihood estimate of μ
σ^2	variance
$\hat{\sigma}^2$	maximum likelihood estimate of σ^2
$\boldsymbol{\theta}$	correlation vector of Kriging
ε	convergence tolerance
Superscripts	
—	mass averaged quantity
Subscripts	
min	minimum
max	maximum
1	inlet
2	outlet

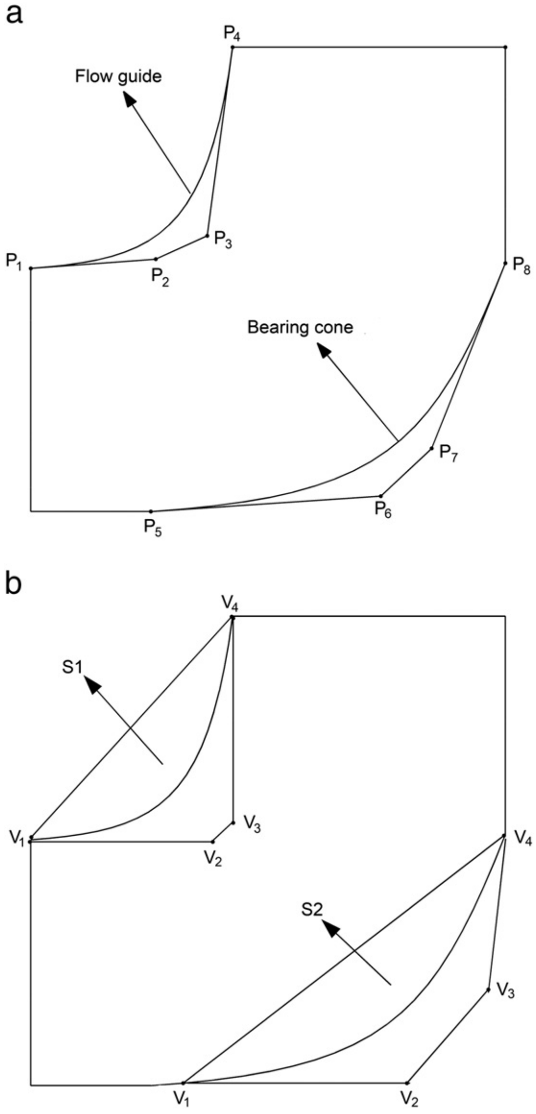

Fig 2. Schematic diagram of (a) geometry parameterization; and (b) design domain.

longitudinal and end wall views of the model are shown in Fig. 1. Detailed dimensions of the model are marked in the figure as well. As shown in Fig. 2(a), two cubic Bezier curves are used to represent the flow guide and the bearing cone profiles, respectively. A cubic Bezier curve is defined by four control points and can be written as

$$D(t) = \sum_{i=1}^{4} P_i B_i(t) \tag{1}$$

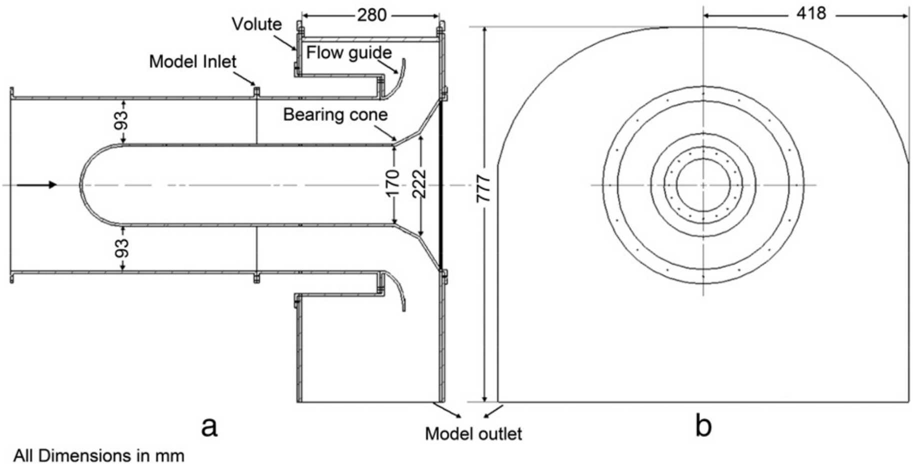

Fig. 1. Schematic diagram of exhaust hood model: (a) longitudinal view, (b) end wall view.