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A topology optimization approach applied to laminar flow machine rotor design

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Abstract

The design of flow machines is still a difficult task, mainly due to the large number of free geometrical parameters involved. Thus, design optimization techniques can be applied to obtain optimized designs of these machines. This work deals with optimization of radial flow machine rotors (pumps and turbine), where a novel methodology for the propeller design is proposed based on the topology optimization method which distributes fluid or solid in a design domain to extremize a defined objective function subjected to some constraints. The design objective is to optimize the shape of the channel between two blades of the rotor to minimize the energy dissipation and vorticity, and minimize or maximize the power in the case of a pump or turbine, respectively. These objective functions are combined in a multi-objective function. A two-dimensional finite element is derived in a rotating frame for modelling the rotor flow behaviour. The modelling predicts the flow field between relative two blades of a rotor without considering the influence of the volute. It is assumed that the fluid is flowing in an idealized porous medium subjected to a friction force, which is proportional to the fluid velocity and the inverse local permeability. A porous flow model is introduced with a continuous (grey) permeability design variable for each element that defines the local permeability of the medium and allows the transition between fluid and solid property. The design optimization problem is solved by using the method of moving asymptotes (MMA). Numerical examples are presented to illustrate this methodology.

Keywords: Flow machine design; Topology optimization; Rotor design; Vorticity; Power efficiency

1. Introduction

Radial flow machines are predominant for many different applications in industry and other fields. However, the design and performance prediction of these machines is still a difficult task, mainly due to the large number of free geometrical parameters involved. Moreover, the significant cost and time of trial-and-error methods for building and testing prototypes reduce the profit margins of the manufacturers.

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Numerical simulations can provide very precise information about the behaviour of fluid flow in these machines, thus helping engineers to get a comprehensive performance evaluation of a particular design [1,2]. However, the challenge of improving the performance of these machines requires the solution of an inverse-based design optimization problem, in which an oriented search must be conducted to obtain the optimized design.

1.1. Radial flow machines optimization

We can find some works in the literature related to the optimization of flow machines. For example, Lee et al. [3] applies numerical optimization techniques combined with experimental data to redesign the blades of a fan. They adopt blades with aerofoil profiles, and they optimized them by using genetic algorithms. The resulting changes reduce the input power of the fan in 8.8% compared to reference blades.

The singularity method is an important numerical approach to numerically solve the potential flow between blades inside centrifugal impellers and it has been used for many years to analyse the hydrodynamics of impellers of centrifugal pumps. Based on this $2D$ method, Wen-Guang Li [4], develops an inverse problem to design optimized impeller blades of a centrifugal pump. The hydraulic performance is estimated numerically by using Fluent CFD code and the final result has an improvement of more than 5% for hydraulic efficiency. In other work in the field, Anagnostopoulos [5] maximizes the efficiency of a pump by using a numerical optimization algorithm based on the unconstrained gradient approach, by defining as design variables the blade angles at the leading and the trailing edge. The exact location of the best efficiency point of the pump depends on the blade design, and, therefore, it is determined for each set of blade angles, by using a two-dimensional computational code that simulates turbulent flow and calculates the pump performance characteristic curve. The pump performance is predicted numerically based on the results of the impeller section only. As a result, the exit blade angle exhibits a wider optimal region, ranging between 50° and 58°, which is in agreement with theoretical and statistical data. The maximum efficiency of the pump with the optimal blade shape is about 3% higher (from 70.5% to about 73.5%) compared to the standard design.

In a very interesting work, Gölcü et al. [6] optimize the efficiency of a pump by inserting small blade partitions between two blades. They made a comparative study with different number of blades, with or without blade partitions, and by varying the length of the blade splitters (35%, 60% and 80% main blade length). Pump characteristics with and without the blade splitters are obtained experimentally. These results show that blade partitions cause negative effects on the performance of the pump impeller with 6 and 7 blades. When the blade impeller separator has 5 blades, the efficiency increases with the flow until the flow rate 10 l/s. After this, it decreases with the increase of the blade separator length. A higher efficiency and lower power consumption are obtained with 80% of the length of the main blade. At the point of best efficiency energy, savings of 6.6% and an efficiency increase of 1.14% are achieved. This shows that rotor topology can have important influence in the pump performance.

The application of optimization methods for viscous fluid flow problems has been an active area of research for several decades. The goal of optimization is to achieve improved performance for a user-specified goal that is related to certain parameters of fluidic problems.

Topology optimization method distributes fluid or solid in a design domain to extremize a defined objective function subjected to some constraints. The topology optimization method (TOM) for fluids was introduced by Borrvall and Petersson [7] who optimized the channel flow in a 2D Brinkman medium to minimize the dissipated power. The flow modelling is restricted to the incompressible Stokes flow, neglecting the influence of inertia. In order to relax the optimization problem from an integer (black–white) problem where either fluid or solid property is allowed in an element, a porous flow model is introduced with a continuous (grey) permeability design variable for each element. This leads to a design problem where the flow and (almost) non-flow regions are developed by allowing interpolation between the upper and lower values of the permeability [8,9].

The mathematical basis of this model is investigated by Evgrafov [10] who included the limiting cases of pure liquid and solid. A variation of this method is presented by Guest and Prévost [11], where the Stokes and Darcy equations exist as two different models, which are combined and scaled according to the permeability of each element. Furthermore, stabilized finite element analysis is applied to have the velocity and pressure with equal order. Wiker et al. [12] apply topology optimization to find the optimal layout of Stokes and Darcy regions. In their work, the free flow region is described by Stokes equations, and the porous flow by the Darcy equation. This problem can be treated by a generalization of Stokes equations, that is similar to the Brinkman system [7]. However, in Borrvall and Petersson work [7] only the inverse permeability, denoted by κ, is dependent on the design variable, while Wiker et al. [12]