# CFD COUPLED WITH SHAPE OPTIMIZATION - A NEW PROMISING TOOL IN PAPER MACHINE R&D

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## FROM TRIAL-AND-ERROR TO AUTOMATIZED SHAPE OPTIMIZATION

Experimental trial-and-error product development cycles have largely been replaced with computational fluid dynamics (CFD) in many industrial branches. Experiments play still a crucial role in verification of fluid flow models and in validation of final products, but searching of a good design, for example, can base on CFD. So, we have advanced from experimental trial-and-error method to a modern computational trial-and-error method.

CFD is utilized in dimensioning of an object typically such that the best design is chosen from series of potential geometries, which are simulated. The optimal solution may be different, however, to any of those to be tested. When we can express mathematically how good a given design is, that is, we have a cost function depending on the design, then searching of the best design can be formulated as an optimization problem: find an optimal shape of an object such that the cost function is minimized. Therefore, by combining CFD and optimization algorithms we can advance further from the computational trial-and-error method to the automatized CFD based shape optimization method.

## SHAPE OPTIMIZATION

During the last two decades, optimal shape design algorithms have been developed for many structural and mechanical systems from the mathematical and engineering point of view, see, e.g., [6,15], while a few publications have been published about applications in fluid dynamics. Most of the existing literature relevant to shape optimization of fluid flows is in the context of aerodynamics, see, e.g., [1,2,3]. Aerospace and aeronautical engineering deals often with high Reynolds number flows with viscosity being ignored and, thus, the fluid flow is modeled with full potential or Euler equations. However, there are many applications where an inviscid assumption is not valid and the full Navier-Stokes equations should be used. Shape optimization governed by viscous, incompressible flows have been studied, e.g., in [5,7,12]. For further study on numerical methods for shape optimization in fluids, we refer to [15].

A shape optimization algorithm consists of a state equation and a cost function in addition to an optimization algorithm. The state equation is a discretized fluid flow model, i.e., a CFD model for a fluid flow problem in question. The cost function measures quality of the design in a mathematical form. It depends on the solution of the CFD model, which depends on the shape of the flow domain. The flow domain or part of it is described with the help of finite number of design parameters, which are optimized. The optimization algorithm can be, in principle, any of well-known methods: Gradient method, Conjugate-Gradient method, Quasi-Newton method, etc. Of course, convergence of methods is depending on an optimization problem and cannot be quaranteed a-priori.

In Valmet we have been using shape optimization methods together with CFD for some years designing of the headbox being the most important application. The headbox is the first component in paper making process on a paper machine, located at the wet end. Fluid flow phenomena taking place in the headbox determine largely the quality of produced paper, for example, the basis weight and the fiber orientation variations. The first flow passage in the headbox is a tapered header. It is designed to distribute fiber suspension (wood fibers, filler clays and chemicals mixed in water) such that a produced paper will have optimal basis weight (thickness) and fiber orientation across the width of a paper machine. Our shape optimization problem considered in this paper is to find optimal tapering of the header such that the outlet flow rate distribution from the headbox is optimal resulting in optimal paper quality.

## SENSITIVITY ANALYSIS

When gradient-based optimization algorithms are used in shape optimization, a gradient of the cost function is needed to describe sensitivity of the cost function with respect to changes in a shape of the flow domain. A straightforward way is to use finite differences to approximate the gradient. If the number of the design parameters is N, the finite difference approximation requires N solutions of the CFD model in order to obtain the gradient consisting of N components. Alternatively, the gradient can be obtained by solving an adjoint state equation [13,14,16]. Advantage of the adjoint state technique is that only one solution of a linear adjoint state equation is needed which is noticeable more efficient than solving N nonlinear CFD problems in the difference approximation. But, differentiation of the CFD model resulting the adjoint state equation is not a trivial task.

When the cost function gradient is approximated by finite differences, calculation of each component can be done independently and parallel with a maximal speed-up factor on multi-processor computer. An optimization algorithm may require solving of the CFD model also in one dimensional optimization step. Therefore whole computational time may not be speeded up with the number of processors. For example, let us assume that the number of design parameters and processors is same (N=8, for instance), one dimensional optimization requires 5 solutions of the CFD model, and the whole optimization requires 10 steps. Then 10*(8+5)=130 solutions of the CFD model is needed. On a parallel computer this requires 10*(1+5)=60 steps, i.e., parallel simulation is about 2 times faster than serial one. When the size of the problem increases, also the speed-up factor increases towards the number of the processors assuming that the one dimensional optimization step is independent of the size of the problem.

## CFD MODEL

Modeling of the fluid flows in the headbox is based on the well-known fluid flow models, i.e., the Navier-Stokes equations and the $k\varepsilon$ turbulence model. However, the headbox presents some special difficulties in modeling the fluid flow, because the fluid flows from the header to an equalising chamber through a manifold tube bank consisting of hundreds of small identical tubes. Thus, the manifold tube bank must be taken into account on the average. This has been done by replacing the tube bank by a homogeneous effective medium, which results in a non-linear third type of outflow boundary condition depending on the geometry of the tubes. A detailed description about modeling of the headbox flows and derivation of the homogenised outflow boundary condition is given in [8,10,11].

It is important that both the numerical methods and fluid flow models are accurate for shape optimization to work properly. Shape optimization requires naturally that the shape of a flow domain can be handled flexibly and with high precision. Our choice is a finite element method (FEM), more precisely, a stabilized finite element method [4], which has been found to be one of the most accurate and stable finite element method for CFD problems. Furthermore, shape optimization together with CFD can lead to the best solution in practice only if the CFD model predicts flow phenomena accurately enough. Therefore attention has been paid to the accuracy of numerical methods and verification of the models. The efficiency of numerical algorithms is also important in order to reduce computing time, especially when we consider that a typical optimization requires in the order of one hundred CFD simulations. Computational time is minimized by using fast solvers for algebraic systems and parallel computing in sensitivity analysis [9].

## NUMERICAL EXAMPLE

As mentioned earlier, our test case in this paper is searching of optimal tapering of the header. The header is modelled here two-dimensionally whereupon tapering depends only on the shape of the back wall of the header. The initial back wall and the resulting outlet flow rate profile are indicated by the dotted line in Figure 1. Relative variation in the flow rate profile is about 2/100. Then, the back wall is parametrized by defining 10 design variables, which are optimized. After shape optimization, the flow rate profile is quite even, relative variation being only in the order of 1/1000. Variation is not decreased only in the narrow region in the beginning of the header. This is due to boundary layer phenomena in the inlet tube, which can not be avoided by varying the opposite back wall.

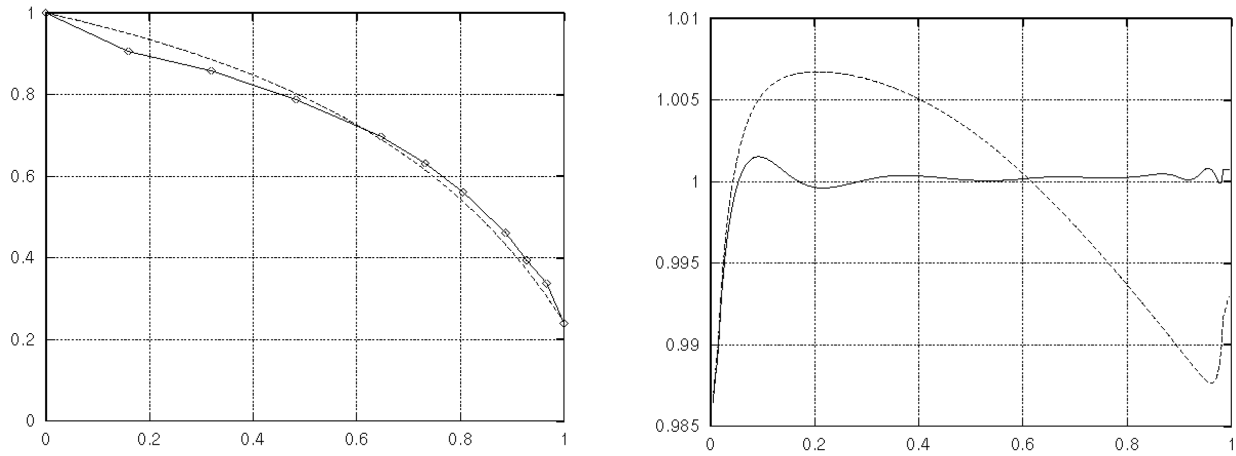


*Figure 1. Initial and optimized shape of the dividing manifold (on the left) and the resulting initial and optimized outlet flow rate profile (on the right).*

## CONCLUSIONS

In addition to same upwinding, stability, convergence, etc. problems than in traditional CFD, shape optimization includes some specific difficulties, convergence of optimization algorithms and accurate enough calculation of the cost function gradient to mention some of them. Shape optimization together with CFD is scientifically challenging problem. It has also proven to be promising new tool in every-day designing problems and it has been utilised in designing paper machine headboxes for several years in Valmet.

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