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Shape optimization with computational fluid dynamics

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Abstract

In many product design and development applications, computational fluid dynamics CFD has become a useful analytical simulation tool. CFD simulations are quite useful in predicting several response parameters for a given design condition. However, like any analysis tool CFD simulations provide limited insight into the design space and the changes needed to find the optimum design parameters.

This paper deals with the shape optimization of fluid flows using CFD and numerical optimization techniques. By integrating a commercial optimization code with a CFD code, a CFD shape optimization tool was developed. To study the effectiveness of the developed tool and its ability to produce results with reasonable CPU time, the shape optimization of an airfoil and S-shaped duct are studied with different numbers of design variables. The developed shape optimization tool along with the optimization and CPU time results are discussed.

Keywords: Computational fluid dynamics; *VisualDOC/DOT*; Sequential quadratic programming

1. Introduction

While a considerable effort of research and development went in shape optimization of solids and structures, very few efforts were directed to the shape optimization of fluids where significant impact on the designs can be achieved [1–5]. With recent research and code development efforts in the area of computational fluid dynamics, CFD has proven to be useful in supporting product design and development in many industrial applications. For many product designs where fluid flow simulations are needed, CFD analyses has proven to be quite useful in predicting the flow pattern for a given set of design parameters. Considering the modeling efforts and computational resources needed, CFD simulations are not usually used to the full ability of truly optimizing the design. With the advances in CFD there is a need for using the full potential of the developed analytical tools in optimizing fluid flow patterns and responses.

Most of CFD analyses and optimization efforts since the early 1970s have focused on aerospace design problems [6–8]. One of the automotive applications is the work by Choi and Kim [9], who coupled CFD simulations with numerical optimization techniques to optimize the design of a low noise automotive cooling fan.

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The high computational expense of real-world flow simulations demands that the optimal design be computed with relatively few CFD solutions. To accomplish this, only efficient optimization algorithms can be used. In this paper, a CFD-based optimization methodology is developed by the integration of three software programs. The numerical optimization code *VisualDOC/DOT* [10,11], the CFD computational code Chaos and the surface geometry generation code Prime. These three codes were combined to produce a CFD shape optimization capability. The optimization capability is tested for its applicability and CPU time using an airfoil and S-shaped outlet duct.

2. Design optimization process

The general constrained nonlinear optimization problem can be stated as:

Find the set of design variables, X_i, $i=1, N$, contained in vector X, that will

$$\text{Minimize}: F(X) \quad \text{Objective function} \tag{1}$$

Subject to:

$$g_j(X) \le 0, \quad j = 1, M \quad \text{Inequality constraints} \tag{2}$$

$$h_k(X) = 0, \quad k = 1, L \quad \text{Equality constraints} \tag{3}$$

$$X_i^L \le X_i \le X_i^U, \quad i = 1, N \quad \text{Side constraints} \tag{4}$$

The vector X is referred to as the vector of design variables. Eq. (1) defines the objective function that depends on the values of the design variables, X. Eqs. (2) and (3), are inequality and equality constraints, respectively, and Eq. (4) defines the region of search for the minimum. The bounds defined by Eq. (4) are referred to as side constraints.

In this work, *VisualDOC/DOT*, numerical optimization software [10,11], is used to solve the constrained optimization problems. The optimum solutions of the CFD-based optimization methodology is achieved by the integration of three major software programs: *VisualDOC/DOT*, numerical optimization software, the interface code *Prime* is used to produce the surface geometry for the set of design variables supplied by the optimization program. The in house CFD code *Chaos* is used to perform the CFD simulation. The design optimization process of Fig. 1 is achieved by linking the three codes with the help of a main driver computer program. The main program calls Chaos and Prime to evaluate the objective function. *VisualDOC/DOT* then updates the design variable values while searching for the optimum. Some additional computer programs are developed to facilitate the communication between these codes. Fig. 1, shows the overall optimization strategy. The generation of *VisualDOC/DOT* optimized design data follows the following steps:

- Start with a set of initial design parameters.
- Generate analysis data first by using *CHAOS*. Analyze the problem using this analysis data, and make the analysis output available.
- Provide the input file for *VisualDOC/DOT* from the analysis output.
- Call *VisualDOC/DOT* to get the output file for this iteration.
- Modify the analysis input by using the output file of *VisualDOC/DOT*.
- Rerun the analysis, until the whole process converges.

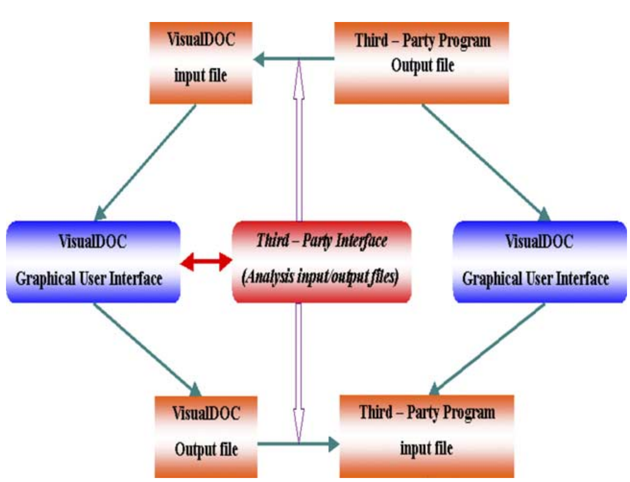

Fig. 1. *VisualDOC/DOT* interface with other software.

3. Shape optimization case studies

To study the applicability of the developed tool and its ability to produce results with reasonable CPU time, the shape optimization of an airfoil and S-shaped duct with circular cross-sections were studied with different numbers of design variables.

3.1. Shape optimization of an airfoil

The shape of an airfoil to be optimized is shown in Fig. 2. The objective is to find an optimum shape for the airfoil so that the pressure losses due to both skin friction and turning of the flow in the bends are minimized. The design variable X_2 is chosen to control the profile. The optimization problem can be summarized as follows:

$$\text{Minimize}: \ \Delta P$$

$$\text{Subject to}: \ G_1 = 1 - X_2 < 0$$

Sequential Quadratic Programming (SQP) algorithm of *VisualDOC/DOT* was used to solve the constrained optimization problem above. The constraint function G_1 represents design variable relationship that should be maintained in order to guarantee a robust construction of CAD surfaces.

The optimization calculations were performed on a SUN workstation. The optimization process took 110.5 h of CPU time to converge. A total of five SQP optimization design iterations were required and 54 function calls were performed during the optimization process. Fig. 3 shows the history of the objective function and the design variable. The optimal shape is obtained in three iterations.

Fig. 4 shows the initial and optimum shapes. It is important to note that although the skin friction losses are proportional to the length and the optimum shape is longer than the initial, the pressure losses due to the curvature are more severe than skin friction losses. The additional length in the optimum shape has allowed the formation of more gradual turns in the bend.

3.2. Shape optimization of an S-shaped duct

An S-shape duct with circular cross-sections was used as a test case. The path–line curve in Fig. 5, is defined in

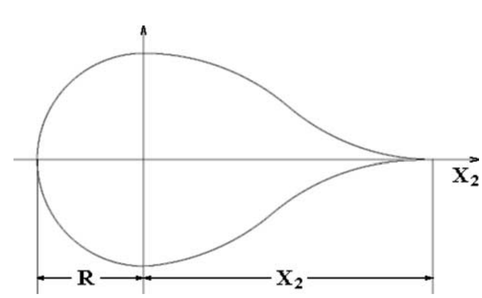

Fig. 2. The airfoil shape and design variable.