Hydro-structural Optimization of a 3-D Hydrofoil

Nitin Garg, Dept. of Naval Arch. and Marine Eng., University of Michigan, gargn@umich.edu
Gaetan K. W. Kenway, Dept. of Aerospace Eng., University of Michigan, kenway@umich.edu
Joaquim R. R. A. Martins, Dept. of Aerospace Eng., University of Michigan, jrram@umich.edu
Yin Lu Young, Dept. of Naval Arch. and Marine Eng., University of Michigan, ylyoung@umich.edu

Long Abstract

Introduction

With recent advances in the computational capability, computational fluid dynamics (CFD) modeling is routinely used for engineering analysis to study the hydrodynamic performance of the marine propulsors such as hydrofoils, propellers, and turbines. However, there is still a lack of efficient and robust high-fidelity design-optimization tools that can be used in the initial and intermediate stages of the design. In previous work [1], we presented a Reynolds-Averaged Navier–Stokes (RANS)-based design-optimization tool capable of handling large number of design variables (of the order of 100) to optimize the shape of an hydrofoil. The objective of that optimization was to minimize the drag coefficient, C_D, and to avoid cavitation for a given lift coefficient, C_L. However, fluids and structures are tightly coupled disciplines in propulsor design, as slight changes in the geometry can lead to significant changes in the hydrodynamic performance and internal stress distributions. Thus, in the present work, we present a 3-D design-optimization tool for the coupled static hydro-structural optimization of an hydrofoil.

1. Methodolgy

In a recent study [2], it was found that continuous dynamic shape change (morphing) of the trailing edge geometry of a foil can lead to fuel savings in the range of 5% to 10% throughout the operation of a commercial fixed wing aircraft. However, while the advantage in aircraft operations has been studied, maritime applications of morphing surfaces bring several other challenges such as higher loading, stronger fluid structure interaction, as well as potential susceptibility to free-surface and cavitation effects. The objective of this paper is to perform high-fidelity hydro-structural design optimization of the RAE 2822 hydrofoil with over 200 shape and material variables.

To achieve the objective, the tool used is modified from previously developed multidisciplinary design optimization (MDO) of Aircraft Configurations with High-fidelity (MACH) [[3], [4]]. The CFD solver used in this work is the structured multi-block compressible flow solver SUMad [5], and the structural solver is the toolkit for the analysis of composite structures (TACS) [6]. In [1], the compressible flow solver SUmb was extended to solve for nearly incompressible flows for Mach number in the order of 0.01, a cavitation constraint was added and the solution was validated against the experimental results.

To handle large number of design variables efficiently, the optimization algorithm used in this paper is sparse nonlinear optimizer (SNOPT) [7]. SNOPT is a gradient-based optimizer that implements a sequential quadratic programming (SQP) method. It can handle large-scale nonlinear optimization problems with thousands of constraints and design variables. For gradient calculation, the adjoint method is used in this paper, as it is highly efficient and accurate.

2. Preliminary Results and Conclusion

In this section, we present the results for a cantilevered tapered RAE 2822 hydrofoil with a 14 m span and a 3.25m mean chord at a Reynolds number of 1.0×10^6. In [1], we established that hydrodynamic shape optimization of a morphing RAE 2822 hydrofoil can lead to reduction in drag coefficient, C_D, by at least 20% for a given C_L. In the current work, we check for the structural considerations of the optimized foil by carrying out coupled hydro-structural optimization. For the purpose of this work, we restricted our hydrofoil to be made of solid Nickel Aluminum Bronze (NiAlBr), which is a common material used in marine propulsors, and constrained the material stress of the optimized shape against the fatigue strength of NiAlBr with a factor of safety of two.

In Figure 1, we show a comparison between the results for a RAE 2822 hydrofoil obtained by hydrodynamic shape optimization only and the result of a coupled static hydro-structural optimization. For a given C_L of 1.0, the difference in C_D for the two optimized foil was only 1.3%. However, to meet the stress constraints, the foil needed to be thicker in the outboard sections along the span in case of coupled hydro-structural optimization, as observed from C_p plots and sectional geometry plots along the span in Figure 1c. In Figure 1b, the difference between the stress coefficient contours, i.e., the fraction of von-Mises stress (σ_v) to fatigue stress (σ_f) of NiAlBr, of hydro-structural optimization and hydrodynamic optimization is presented. In the full paper, more thorough study of the hydro-structural optimization will be presented.

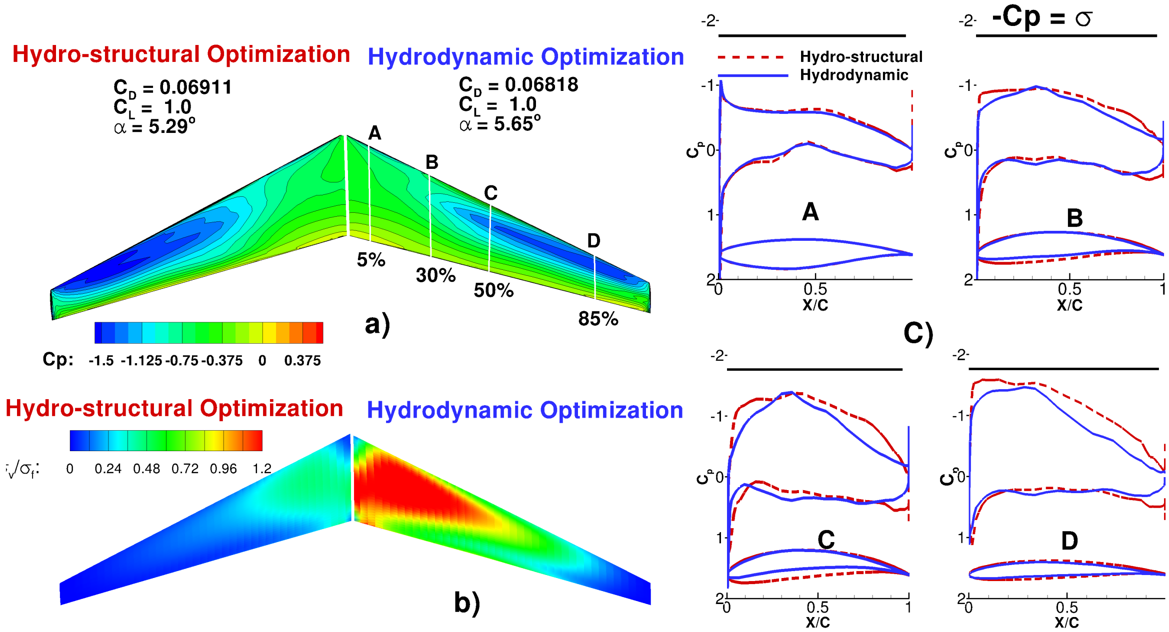

Figure 1. Comparison between hydro-structural optimization and hydrodynamic optimization for RAE 2822 hydrofoil at C_L of 1.0 for $Re = 1.0 \times 10^6$. a) C_p (pressure coefficient) contours plot are displayed for hydro-structural optimized foil and hydrodynamic optimized foil. The pressure coefficient (C_p) contours look fairly similar with slight increase in drag for hydro-structural optimization. b) Difference between the stress coefficient contours (σ_v/σ_f), i.e., the fraction of von-Mises stress to fatigue stress of NiAlBr, of hydrodynamic optimization and hydro-structural optimization is presented. A high stress region can be noticed in the hydrodynamic optimization. c) At various sections along the span of the foil, the difference in C_p and geometry are displayed. The hydro-structural optimization required the sections at B (30%Z/S) and C (50%Z/S) to be thicker to meet the factor of safety requirement against the fatigue strength of NiAlBr. The black solid line represents the cavitation number constraint line, set at 1.8 for both the cases.

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