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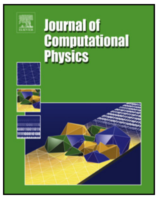

Time dependent adjoint-based optimization for coupled fluid–structure problems

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ABSTRACT

A formulation for sensitivity analysis of fully coupled time-dependent aeroelastic problems is given in this paper. Both forward sensitivity and adjoint sensitivity formulations are derived that correspond to analogues of the fully coupled non-linear aeroelastic analysis problem. Both sensitivity analysis formulations make use of the same iterative disciplinary solution techniques used for analysis, and make use of an analogous coupling strategy. The information passed between fluid and structural solvers is dimensionally equivalent in all cases, enabling the use of the same data structures for analysis, forward and adjoint problems. The fully coupled adjoint formulation is then used to perform rotor blade design optimization for a four bladed HART2 rotor in hover conditions started impulsively from rest. The effect of time step size and mesh resolution on optimization results is investigated.

1. Introduction

In the recent past, the use of adjoint equations has become a popular approach for solving aerodynamic design optimization problems based on computational fluid dynamics (CFD) [1–9]. Adjoint equations are a very powerful tool in the sense that they allow the computation of sensitivity derivatives of an objective function to a set of given inputs at a cost which is essentially independent of the number of inputs. This is in contrast to the brute-force finite-difference method, where each input or design variable has to be perturbed individually to obtain a corresponding effect on the output. This is a tedious and costly process which is impractical when there are a large number of design variables or inputs. Another major shortcoming of the finite-difference method is that it suffers from step-size limitations which affect the accuracy of the computed gradients.

While the use of adjoint equations is now fairly well established in steady-state shape optimization, only recently have inroads been made into extending them to unsteady flow problems. Unsteady discrete adjoint-based aerodynamic shape optimization was initially demonstrated in the context of two-dimensional problems by Mani and Mavriplis [10] and also by Rumpfkeil and Zingg [11]. Preliminary demonstration of the method's feasibility in three-dimensional problems was done by Mavriplis [12]. Full implementation in a general sense and application to large scale problems involving helicopter rotors was then carried out by Nielsen et al. in the NASA FUN3D code [13–15].

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Nomenclature

Acronyms

CFD	Computational Fluid Dynamics	
CSD	Computational Structural Dynamics	

Symbols

a	Speed of sound	$\mathrm{m\,s^{-1}}$
A	Rotor disk area, πR^2	$\mathrm{m^2}$
c	Rotor chord	m
C_D	2-D drag coefficient	
Cd_0	Profile drag coefficient	
C_L	2-D lift coefficient	
C_M	2-D pitching moment coefficient	
C_p	Pressure coefficient	
C_f	Skin friction coefficient	
C_T	Rotor thrust coefficient, $T/(\rho A\Omega^2 R^2)$	
C_Q	Rotor shaft torque coefficient, $Q/(\rho A\Omega^2 R^3)$	
r	Radial distance of a rotor spanwise station	m
R	Rotor radius	m
Re	Reynolds number, Vc/ν	
V	Velocity	$\mathrm{m\,s^{-1}}$
U_∞	Freestream velocity	$\mathrm{ft\,s^{-1}}$
M	Mach number, V/a	
M_∞	Freestream Mach number, U_∞/a	
M_{tip}	Rotor tip Mach number, U_{tip}/a	
α	Sectional angle of attack	deg
α_s	Shaft tilt angle	deg
θ_0	Collective pitch	deg
ν	Kinematic viscosity	$\mathrm{m^2\,s^{-1}}$
ρ	Flow density	$\mathrm{slugs\,m^{-3}}$
ψ	Azimuth angle	deg
Ω	Rotor rotational speed	$\mathrm{rad\,s^{-1}}$
Δt	Time step size	deg

Since engineering optimization is an inherently multidisciplinary endeavor, the next logical step involves extending adjoint methods to multidisciplinary simulations and using the obtained sensitivities for driving multidisciplinary optimizations. In the context of fixed and especially rotary wing aircraft, aeroelastic coupling effects can be very important and must be considered in the context of a successful optimization strategy.

The coupling of computational fluid dynamics (CFD) and computational structural dynamics (CSD) and the use of sensitivity analysis on such a system has been addressed in the past primarily from a steady-state standpoint [16,17]. Until now, relatively little work has been done addressing unsteady aeroelastic optimization problems, mainly due to complexities in the linearization of coupled time-dependent systems. In previous work [18], we have derived the fully coupled adjoint problem for a two-dimensional aeroelastic airfoil problem and demonstrated the use of adjoint-derived sensitivities for performing time-dependent aeroelastic optimization including flutter suppression. This formulation was subsequently extended to time-dependent three-dimensional aeroelastic problems in Refs. [19–21]. This work built upon a previously demonstrated time-dependent aerodynamic optimization capability that was applied to helicopter rotors in Ref. [22] through the addition of a Hodges–Dowell type beam finite-element model to simulate the rotor structure, and the development of the fully coupled discrete adjoint of the resulting aeroelastic system. This paper recapitulates the formulation, implementation, and verification of the adjoint sensitivity analysis approach for time dependent coupled aeroelastic problems developed in Ref. [20]. In addition, the current work also demonstrates the effectiveness of using this approach for performing aeroelastic optimization of a representative rotorcraft configuration.

Because high fidelity time-dependent optimization represents a computationally intensive approach, obtaining a suitable optimization result with manageable computational requirements is an important consideration. Therefore, a particular aspect of this work considers the suitability of optimization results obtained on relatively coarse meshes and using larger time steps, in order to reduce overall computational effort.

2. Aerodynamic analysis formulation

2.1. Flow solver analysis formulation

The base flow solver used in this work is the NSU3D unstructured mesh Reynolds-averaged Navier–Stokes solver. NSU3D has been widely validated for steady-state and time-dependent flows and contains a discrete tangent and adjoint sensitivity capability which has been demonstrated previously for optimization of steady-state and time-dependent flow problems. As such, only a concise description of these formulations will be given in this paper, with additional details available in previous references [12,22,23]. The flow solver is based on the conservative form of the Navier–Stokes equations which may be written as:

$$\frac{\partial \mathbf{U}(\mathbf{x},t)}{\partial t} + \nabla \cdot \mathbf{F}(\mathbf{U}) = 0 \tag{1}$$

For moving mesh problems these are written in arbitrary Lagrangian–Eulerian (ALE) form as:

$$\frac{\partial V\mathbf{U}}{\partial t} + \int\limits_{dB(t)} [\mathbf{F}(\mathbf{U}) - \dot{\mathbf{x}}\mathbf{U}] \cdot \mathbf{n}\, dB = 0 \tag{2}$$