

Industrial Applications of Aerodynamic Shape Optimization

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Nomenclature

A	Hessian Matrix / Operator	N	Number of Design Variables
AR	Wing Aspect Ratio = $\frac{b^2}{S_{ref}}$	R	Flow-Equation Function
b	Wing Span	$RANS$	Reynolds-Averaged Navier-Stokes
\mathcal{B}	Shape Function Basis	RCS	Reaction Control System
CFD	Computational Fluid Dynamics	Re	Wing Reynolds number based on C_{ref}
C_D	Drag Coefficient = $\frac{Drag}{q_\infty S_{ref}}$	Re_θ	Attachment Line Reynolds number
C_L	Lift Coefficient = $\frac{Lift}{q_\infty S_{ref}}$	S_{ref}	Wing Reference Area
C_{ref}	Wing Reference Chord	UAV	Unmanned Aerial Vehicle
$count$	Drag Coefficient Unit = 0.0001	x	Independent Spatial Variable
\mathcal{F}	Surface Defining Function	q	Dynamic Pressure = $\frac{1}{2}\rho V^2$
\mathcal{G}	Gradient of Cost Function	w	Flow Variable
H	Estimate of Inverse Hessian Matrix	λ	Wing Taper Ratio; Search Step Parameter
HP	Horse Power	$\Lambda_{c/4}$	Wing Quarter-Chord Sweep
I	Objective or Cost Function	∞	Infinity
$KEAS$	Knots Equivalent Air Speed	δ^*	First Variation of
MPH	Mile Per Hour	$\mathcal{O}(*)$	Order of
		$(*)^{-1}$	Inverse Matrix of

1 Introduction

This is the second of two lectures prepared by the authors for the von Karman Institute that deal with the subject of aerodynamic shape optimization. In our first lecture we introduced some theoretical background on optimization techniques commonly used in the industry, applied these approaches to a couple of very simple model problems, compared the results of these schemes, and discussed their merits and deficiencies as they relate to the class of aerodynamic shape optimization problems the authors deal with on a regular basis. In this lecture, we illustrate how the gradient of a complex system of nonlinear partial differential equations can be obtained for about the same computational cost as that of the cost function, and we provide a set of sample applications.

In an airplane design environment, there is no need for an optimization based purely on the aerodynamics of the aircraft. The driving force behind (almost) every design change is related to how the modification

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improves the vehicle, not how it enhances any one of the many disciplines that comprise the design. Although we focus this lecture on the aerodynamics of an airplane, we also include the means by which other disciplines are linked into and affect the aerodynamic shape optimization subtask. Another characteristic of the problems we typically (but not always) work on is that the baseline configuration is itself within 1-2% of what may be possible, given the set of constraints that we are asked to satisfy. This is certainly true for commercial transport jet aircraft whose designs have been constantly evolving for the past half century or more. The sample applications provided herein do not fall into this category. Quite often the problem can be very constrained; this is the case when the shape change is required to be a retrofitable modification that can be applied to aircraft already in service. Occasionally, we can begin with a clean slate, such as in the design of an all-new airplane. And the problems cover the full spectrum of studies in between these two extremes.

Let's note a couple of items about this setting. First, in order to realize a true improvement to the baseline configuration, a high-fidelity and very accurate computational fluid dynamics (CFD) method must be employed to provide the aerodynamic metrics of lift, drag, pitching moment, spanload, etc. Even with this, measures should be taken to estimate the possible error band of the final analyses; this discussion is beyond the scope of these lectures. Figures 1-2 illustrate the class of aircraft and the level of detail the first author addresses every day. These Navier-Stokes CFD solutions are conducted on full-up cruise configurations, complete with wing, fuselage, engine groups, empennage, flap-support fairings, and winglets. The engine groups include a pylon, nacelle, core-cowl, shelf, and bifurcation flows. Although not obvious in these images, various fillets are also included. Finally, the CFD calculations are performed at prescribed lifting conditions by altering angle-of-attack, and are trimmed to specified center-of-gravity locations by adjusting the horizontal tail incidence. This level of detail is needed to achieve an accuracy on the absolute performance of the aircraft that is within 1% of flight test data. However, this is what is required to improve the performance of the aircraft by 1-2% without a numerical optimization yielding a false positive. The second item to consider is related to the definition of the design space. A common practice is to use a set of basis functions which either describe the absolute shape of the geometry, or define a perturbation relative to the baseline configuration. In order to realize an improvement to the baseline shape, the design space should not be artificially constrained by the choice of the set of basis functions. This can be accomplished with either a small set of very-well-chosen basis functions, or with a large set of reasonably-chosen basis functions. The former approach places the burden on the user to establish an adequate design space, the later approach places the burden on the optimization software to economically accommodate problems with large degrees of freedom. Over the past decade, the authors have focused on solving the problem of aerodynamic shape optimization utilizing a design space of very large dimension. Our principal motivation for addressing the problem of large number of design variables is two fold. The first is to provide a situation where the design space never needs to be artificially constrained. The second is to allow us the flexibility to automatically set up the design space within the optimization software at the highest dimensionality supported by the discrete numerical simulation. In doing so, the aerodynamic shape optimization software based on these concepts allow the user to run optimizations immediately after set up of the analysis inputs are complete. This speeds time-to-first-optimization and minimizes the human errors associated with defining a design space. Furthermore, aerodynamic shape optimizations based on either the Euler or Navier-Stokes equations can be run on relatively inexpensive computer equipment.

The next section provides an overview of aerodynamic optimization. We develop an efficient evaluation for the gradient; this is based on solving an adjoint equation. A brief review of the search methods we utilize are then included. Following this discussion, we present a few selected case studies. These sample applications are all on design activities that we have been involved with; they include a Mars aircraft, a Reno Racer, and an aero-structural optimization of a generic B747 wing/body configuration.

2 Aerodynamic Design Trades

The objective of aerodynamic design is to produce a structurally feasible shape with sufficient carrying capacity, which achieves good aerodynamic performance.

For example, consider the generic task of delivering a payload between distant city pairs. The Breguet Range equation, which aptly applies to long-range missions of jet aircraft, is:

$$Range = \frac{ML}{D} \frac{a}{SFC} \ln \left(\frac{W_0 + W_f}{W_0} \right). \quad (1)$$