Chapter 5
Efficient Deterministic Approaches for Aerodynamic Shape Optimization

Nicolas R. Gauger

Abstract Because detailed aerodynamic shape optimizations still suffer from high computational costs, efficient optimization strategies are required. Regarding the deterministic optimization methods, the adjoint approach is seen as a promising alternative to the classical finite difference approach. With the adjoint approach, the sensitivities needed for the aerodynamic shape optimization can be efficiently obtained using the adjoint flow equations. Here, one is independent of the number of design variables with respect to the numerical costs for determining the sensitivities. Another advantage of the adjoint approach is that one obtains accurate sensitivities and gets rid of the laborious tuning of the denominator step sizes for the finite differences.

Differentiation between continuous and discrete adjoint approaches is noted. In the continuous case, one formulates the optimality condition first, then derives the adjoint problem and finally does the discretization of the so-obtained adjoint flow equations. In the discrete case, one takes the discretized flow equations for the derivation of the discrete adjoint problem. This can be automated by so-called algorithmic differentiation (AD) tools.

The different adjoint approaches will be explained for single disciplinary aerodynamic shape optimization first and then their extension to multidisciplinary design optimization (MDO) problems will be discussed for aerostructure cases. Finally, we will discuss the so-called one-shot methods. Here, one breaks open the simulation loop for optimization.

Nicolas R. Gauger
German Aerospace Center (DLR), Institute of Aerodynamics and Flow Technology,
Lilienthalplatz 7, 38108 Braunschweig, Germany
together with
Humboldt University Berlin, Department of Mathematics,
Unter den Linden 6, 10099 Berlin, Germany
(e-mail: Nicolas.Gauger@dlr.de)
Nomenclature

\[(x, y) \in \mathbb{R}^2\] cartesian coordinates
\[(\xi, \eta) \in [0, 1]^2\] body fitted coordinates
\(D \subset \mathbb{R}^2\) flow field domain
\(\partial D = B \cup C\) flow field boundary
\(B = \{ (\xi, 1) \}\) farfield
\(C = \{ (\xi, 0) \}\) solid wall
\(n = \begin{pmatrix} n_x \\ n_y \end{pmatrix} \perp D\) outward pointing normal unit vector
\(\alpha\) angle of attack
\(\rho\) density
\(v = \begin{pmatrix} u \\ v \end{pmatrix}\) velocity
\(p\) pressure
\(E\) specific total energy
\(H\) total enthalpy
\(M_\infty\) Mach number
\(\gamma\) ratio of specific heats
\(\gamma_\infty\) ... at free stream
\(C_{\text{ref}}\) cord length
\(C_p\) pressure coefficient
\(C_D\) drag coefficient
\(C_L\) lift coefficient
\(C_m\) pitching moment coefficient
\((x_m, y_m)\) pitching moment’s reference point
\(I\) cost function
\(-d(I)\) adjoint boundary condition’s RHS on \(C\)
\(X \in \mathbb{R}^n\) vector of design variables
\(Z\) displacement field

5.1 Introduction

In aerodynamic shape optimization, the task of computing sensitivities is essential for the application of gradient-based optimization strategies. Gradient computations for a given cost function \(I(X)\), for a design vector \(X\) out of a defined design space, can generally be done with several methods.

One way is the finite difference method (FD), which approximates the components of the gradient by difference quotients of the cost function evaluated for the initial aerodynamic shape as well as the shapes generated by perturbations of the design variables, for a given step size in the design space. Hence, the computational effort for the gradient approximation using finite differences is proportional to the number of design variables. Therefore, problems with this method occur if the computation of the cost function is extremely expensive or if there are many design variables. Again, the finite differences are just approximations and therefore one has to take care of the accuracy. As we will see in Sect. 5.4, step size tuning requires a lot of effort as well.

An alternative are the so-called adjoint methods that include two kinds of approach: continuous and discrete adjoint approaches.

In the continuous case one formulates the optimality condition first, then derives the adjoint problem and finally does the discretization of the so obtained adjoint flow equations. The continuous adjoint method was first used