7 Applications of Boundary-Layer Methods: Flows with Separation

7.1 Introduction

The calculation method of the previous chapter is limited to flows without separation. As discussed in Section 5.2, the boundary-layer equations for steady flows become singular at the vanishing of wall shear, and the solutions break down. To avoid the singularity and be able to obtain solutions of flows with separation, it is necessary to solve the equations in the inverse mode.

The same is true for unsteady flows when the boundary-layer solutions experience a singularity as discussed in Section 5.5 and again require an inverse boundary-layer method to continue the calculations past the singularity. Unfortunately our knowledge of unsteady flows, particularly those for boundary-layer equations, is less sound than of steady ones. As we discussed in Section 5.2, in the classical boundary-layer theory, the point of zero wall shear stress coincides with the point of separation, and the equations have singular behavior, but this is not the case in the unsteady theory. As described in [1, 2], for example, flow reversals can occur in unsteady flows without flow separation. It is useful to distinguish one from the other so that flow separation can properly be identified in an unsteady flow when the boundary-layer calculations are performed for a prescribed pressure distribution. It is also useful and necessary to explore the accuracy of the numerical method used to solve the time-dependent boundary-layer equations, especially in regions of flow reversal and separation.

In the following section, we consider a model problem for a thin oscillating airfoil and discuss the evolution of the unsteady boundary layers in the vicinity of its leading edge and the ability of the calculation method to deal with the movement of the stagnation point and with regions of reverse and separated flow. In Section 7.3, we discuss the application of the boundary-layer method to several steady airfoil flows and in Section 7.4 we extend the application to
oscillating airfoils and airfoils subject to ramp-type of motion and compare the calculated results with experimental data.

7.2 Separation and Reattachment Near the Leading Edge of a Thin Oscillating Airfoil

The lift and drag characteristics of airfoils at moderate Reynolds numbers can be affected by separation bubbles which occur close to the leading edge as discussed in [3] and, at high angles of attack, can increase in size to cause stall. The added complexity of unsteady motion such as that associated with the rotor blades of helicopters implies that the flow characteristics are influenced by amplitude and frequency and that, in particular, the stall characteristics can be considerably modified. The investigations reported in [4-10] examined these effects over limited ranges of the parameters, and that of [6,10] provides detailed information on the mechanism of dynamic stall of an oscillating airfoil. It appears that stall is associated with flow reversals in the unsteady boundary-layer and that these may translate downstream or upstream depending upon various parameters including the radius of the leading edge of the airfoil. At some stage in the cycle, stall occurs and is preceded by a vortex which forms close to the surface and is probably associated with a breakdown of the unsteady boundary-layer.

The above physical problems involve laminar, transitional and turbulent flow and their representation requires a calculation procedure that can provide accurate solutions to conservation equations in all regions of flow as well as appropriate transition and turbulence models. Here in this section we are concerned with the ability and accuracy of the calculation method of Chapter 5 to represent the regions of reverse flow and its use in examining the nature of solutions for parameters close to those associated with stall. The emphasis is on regions of flow close to the leading edge of a model problem corresponding to a thin oscillating airfoil with calculations performed (a) for a prescribed pressure gradient and (b) with interaction between solutions of the viscous and inviscid flow equations. With the configuration chosen, an analytical solution for the potential flow equations is available and the inviscid flow method of Chapter 3 is not needed.

7.2.1 Model Problem

Local regions of separated flow are common on thin airfoils at angle of attack and can be important particularly because of their association with the phenomenon of stall. For thin airfoils, the laminar boundary layer grows from the stagnation point and is subjected to an adverse pressure gradient near the leading edge, which causes separation and subsequent transition to turbulent flow.