Separation of Laminar Boundary Layer Induced by Aerodynamic Interference

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Introduction

AERODYNAMIC interference phenomena have been studied for many years. Principally these studies have been directed at situations in which real flow could be approximated by the use of potential theory. Indeed this approximation has served well to estimate both wind tunnel wall effects and the influence of adjacent surfaces on each other, including the interaction that induces a changing aerodynamic load on external stores or pilot escape capsules during their trajectory through the flowfield surrounding the parent aircraft. It is not our purpose to review aerodynamic interference as interpreted using potential theory. The reader interested in that aspect may wish to look up Ref. 1, which is a fairly recent summary of research in aerodynamic interference. Rather, our purpose here is to discuss a class viscous-outer flow aerodynamic interference. With the exception of shock-boundary layer interaction[2,3] and streamline displacement in boundary layers due to probes[4,5] this sort of flow seems not to have received a great deal of attention except for illustrating complex phenomena.[5,6] The present Note deals with separation on a surface covered by a laminar boundary layer. A nearby body causes a pressure gradient on the first surface that, under some circumstances, will in turn lead to boundary-layer separation on the first surface. For the case of flow in a wind tunnel containing a large model, when one uses self-streamlined wind tunnel walls to reduce wall interference, the induced separation is most likely at high-induced pressure gradients near the angle of attack where the airfoil stalls.

The study presented here is based upon the use of simple shapes with laminar boundary layers on the extended surface. An objection based upon the fact that such walls are not likely to have laminar boundary layers in any practical case has considerable merit. Nevertheless, the use of laminar boundary layers allows the phenomenon to be illustrated simply. The quantitative aspects of the situation would clearly be different if the boundary layers are turbulent. The level of the pressure gradient, the distribution of the momentum thickness on the wall, and the size of the parameter defining separation will be different in a turbulent boundary layer. But the qualitative aspects of the situation will be similar, and therein lies the merit of studying the simple case.[6]

The analysis is based on two-dimensional incompressible flow. It will provide the approximation for the separation conditions. Several results will be presented showing circumstances under which external flow-induced separation is possible.

Analysis

For a two-dimensional laminar flow it is well accepted[6] that separation takes place when

$$\lambda = \frac{\Theta^2}{\nu}\frac{dU_e}{ds} = \frac{\Theta^2}{a^2} \qquad Re_a \frac{dU_e/U_\infty}{d(s/a)} = -0.09 \qquad (1)$$

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Note that the coordinate s or s/a is along a streamline in unconfined flow; along a straight wall the coordinate is x, or x/a. The velocity distributions for a source or dipole in a uniform flow may be deduced readily from potential theory. The results are well known[7] and need not be listed.

We note the following: a semi-infinite body approximated by a source in free air has the following properties away from the centerline. The value of q/U_∞ decreases from unity as (x/a) moves from $-\infty$ toward $-x/a$. On the line $-x/a = y/a$, a minimum value of (q/U_∞) occurs. Then (q/U_∞) increases until $x/a = \pm y/a$, where the velocity is maximum. The velocity then decreases and approaches unity as x/a approaches ∞. The same general condition holds for the semi-infinite body near a single wall. However, the velocity increases monotonically in the case of the semi-infinite body between two walls.

The flow past a cylinder exhibits similar properties. That is, the velocity ratio decreases, then increases, is a maximum at $x = 0$, then decreases, reaches a minimum less than unity, and finally increases to unity as (x/a) approaches ∞. Again the same sort of pattern holds for the cylinder plus one wall. The cylinder between two walls generates a velocity field that is always one or greater in value and has a single maximum at $x = 0$. In all these cases the value of the maximum and minimum depends upon s/a and h/a, the nondimensional distance to the wall. In the case of flow past the cylinder the derivative of velocity with respect to x is antisymmetric, so the maximum in the derivative occurs at $x < 0$, followed by a strong minimum at $x > 0$. The latter minimum is followed in turn by a weak maximum (see Table 1).

Reflection on Eq. (1) suggests that if the incoming boundary layer is relatively thick, separation can occur where even a weak minimum exists. Figure 1 shows the variation of $(\Theta^2/a^2)Re_a$ for the source without walls and the distribution of the separation parameter $\lambda/5$. Note this parameter has a maximum negative value. This value is plotted in Figs. 2a-c for three different lengths over which the boundary layer is allowed to grow. This corresponds to a fluid model where the viscosity is zero up to the stated starting point on the wall or streamline of ½H, 2½H and 5H, respectively. The larger bodies represented by source and doublet flow all will have separation, except for the source with two walls. In the case of the source with the streamline replaced by a streamlined wall, which models the self-streamlining wall or "smart wall" tunnel, separation takes place at the point near where the deceleration is a maximum. Separation takes place near the downstream maximum deceleration point for the source and one wall and all the doublet flows. These maximums are at the downstream locations also. The reason that the 2½ height length seems to resist separation (Fig. 2b) is because the local acceleration thins the boundary layer considerably near this point. Note that if the initial value of $(\Theta^2/a^2)Re_a$ is large enough, a point near the forward minimum could also be a separation point. The initial value that would just cause separation at the forward minimum is shown in Table 2.

Table 1 Cases calculated

	Source; semi-infinite body			Doublet; cylindrical-like body		
Wall	No walls	One wall	Two walls	No walls	One wall	Two walls
Notation	S_F	S_1	S_2	D_F	D_1	D_2
at $h/2a$	−2	−2	−2	−2	−2	−2
	−4	−4	−4	−4	−4	−4
		−8	−8		−8	−8

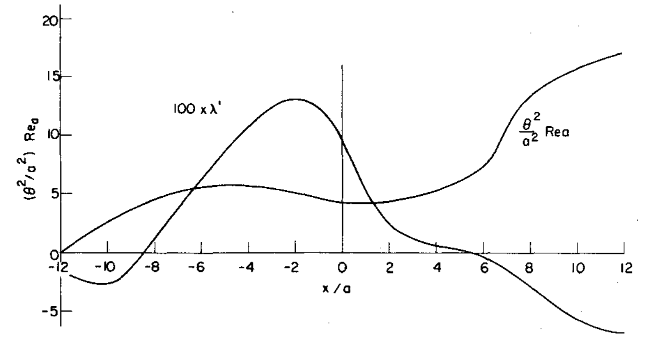

Fig. 1 **Distribution of (Θ^2/a^2) Re_a and μ'—source in free air; $\psi(-a) = -4U_a a$.**

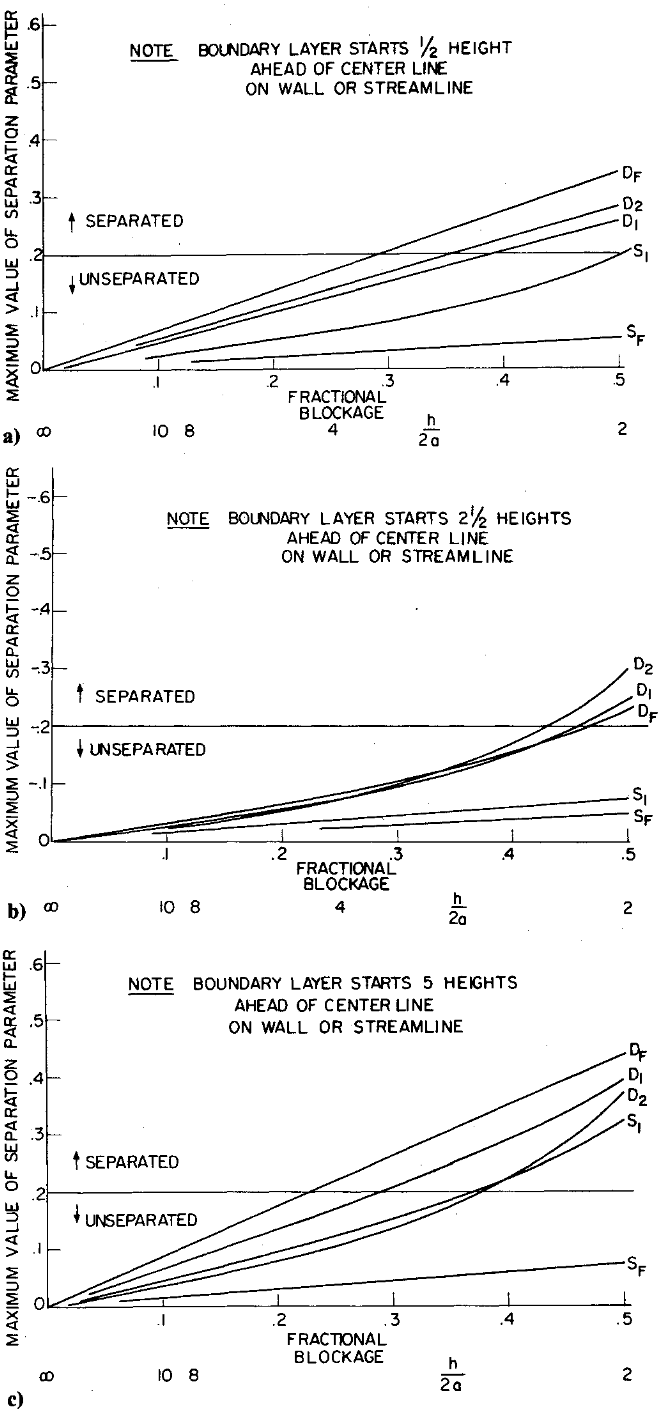

Fig. 2 **Boundary layer starts a) ½ height ahead of centerline on wall or streamline, b) 2½ heights ahead of centerline on wall or streamline, and c) 5 heights ahead of centerline on wall or streamline.**

Table 2 Initial value of $(\Theta^2/a^2)Re_a$ for upstream separation

	Source	Source + 1 wall	Doublet	Doublet + 1 wall	Doublet + 2 walls
−2	24	3.4	66	54	7150
−4	29	9.6	7120	400	Not computed
−8	93	156	−	37.6	Not computed

Note typical blocking in classical wind tunnels is of the order of 5% or less. In that case separation on the wall of the type described here is unlikely to happen. However, use of large models and self-streamlining walls, particularly near stall where gradients could be numerically large, may present problems.

Alternately, in confined flowfields, as may be encountered between an external store and its rack, it is possible that induced separation of this type could exist. This is particularly likely because the store usually extends well in front of the rack and so a relatively thick boundary layer could be expected. Note that it is possible in a confined flow for the aft separation (as in the source plus one wall) to choke or block the flow and to cause the separation point to move well forward. Flow between a wall and any boattail shape generates a deceleration that causes the wall boundary layer to be particularly susceptible to the latter type of induced separation. Finally, below a critical Mach number the results suggest likelihood of separation may be reduced through the use of aerodynamic interference to accelerate the flow locally.

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Sound Radiation From Ducts: A Comparison of Admittance Values

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WHEN considering the radiation from an open duct, it is found that some of the energy is radiated and some reflected (with a phase shift) back down the duct. It is

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