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Flat plate drag reduction by turbulence manipulation

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Abstract. The major objective of the present paper is to delineate the conditions under which a turbulent boundary layer manipulated by the insertion of a passive object may lead to a lower overall drag than in the unmanipulated flow. It is pointed out that almost any device inserted in the boundary layer will lead to a lower *skin friction* drag. Experimental evidence is presented to support this conclusion, which is most easily thought of as characterizing "wall wakes". However when the streamwise extent of the manipulator is not small, the no-slip condition forced on the manipulator boundary modifies the flow through what is here described as the "blade" effect. The presence of this effect may be inferred from experimental data which unambiguously show that a flat plate with a chord c of the order of the boundary layer thickness δ produces the same order of skin friction reduction as a cylindrical rod with a higher wake momentum thickness θ_w. As in general both blade and wake effects are operating simultaneously, available data are analysed in the plane formed by the two variables c/δ and θ_w/δ. This analysis shows that the net drag reduction, if it occurs at all, is quite small, and that its realization demands a blade chord (at zero incidence) larger than about 40 θ_w.

Finally, it is pointed out that if, as often claimed, such manipulators effect a permanent decrease in boundary layer momentum thickness, then sufficiently far downstream where the boundary layer may be expected to have returned to equilibrium, the local skin friction coefficient at any station must be higher than in the unmanipulated flow at the same station because of the lower momentum thickness Reynolds number. It therefore follows that any possible reduction in drag due to the manipulator can only be achieved for certain limited downstream lengths behind the manipulator.

Keywords. Drag reduction; turbulence manipulation; skin friction; wall wakes; blades.

1. Introduction

The extraordinary increases in the price of fossil fuels that have occurred in the last 15 years have directed attention once again to problems connected with the control of turbulent flows. A large part of the resistance offered to the flow of fluids in a variety of technological applications can be traced to the high skin friction drag associated with flow turbulence. Although there are cases where *enhancing* the turbulence levels in a flow may produce beneficial effects, even for the drag, as in the classic experiment of Wieselsberger (in which a ring trip placed on the front of a sphere was shown to reduce the drag of the sphere significantly over a certain Reynolds number range), the subject which has attracted most attention in recent years is the possibility of modifying or manipulating turbulence to reduce the skin friction drag of bodies.

Turbulence may be controlled in many different ways. To begin with, it may be totally *prevented* from occurring. This has been a subject of long-standing interest; work done in the 1950s showed in particular how boundary layer suction could maintain laminar flow on aerodynamic surfaces. For a variety of operational and technical reasons, however, development along these lines was abandoned in the 1960s, but perhaps oil was at that time too cheap for sophisticated fluid-dynamical technologies of drag reduction to be worthwhile on aircraft. More recent work has demonstrated the scientific feasibility of active control of transition (Liepmann & Nosenchuck 1982; Thomas 1983; Strykowski 1986). We are certain that the wave-cancellation ideas that inspire this approach, and other more familiar preventive methods, will be pursued with vigour in coming years.

Another concept is to relaminarize an initially turbulent flow: this is essentially *curative*. It has become clear here that there is a vast number of agencies that can force a turbulent flow back to a laminar or quasi-laminar state. The present authors have in recent years considered these problems at great length (Narasimha & Sreenivasan 1979; Sreenivasan 1981; Narasimha 1983), and if only for this reason we feel that it is unnecessary to discuss the possibilities here once again.

The third concept involves modifying turbulence in some beneficial way; and it is indeed this possibility that is going to be the major concern of the present analysis. An early demonstration of this possibility was perhaps contained in Roshko's (1955) study of the effect of a splitter plate in the wake of a circular cylinder: he found that the base pressure coefficient could be raised approximately from -1.1 to -0.5, implying a substantial reduction in the *pressure* drag of the cylinder. The question is whether similar manipulation is likely to reduce *skin friction* drag on streamlined bodies. The expectation that such reduction might be feasible rests, we believe, on certain basic characteristics of turbulent flows that have emerged from various fundamental studies carried out during the last fifteen years. Among these characteristics are (i) the presence of a considerable degree of order or structure in turbulent shear flows [reviewed in recent years by Cantwell (1981) and Coles (1985) among others], (ii) the production of turbulent energy in "bursts" (Kline *et al* 1967), which show a strong coupling between the outer and inner flows in the boundary layer (Rao *et al* 1971; Narasimha & Kailas 1987, pp. 188–222), and (iii) the long memory of turbulent flows (Clauser 1956; Narasimha & Prabhu 1972). These facts support the tantalizing possibility that appropriate interference with the organized motion in a turbulent boundary layer, active or passive, could lead to favourable effects that will persist for long times or flow distances. Numerous schemes based on this concept have been tried (Bushnell 1983), but few have yet travelled the long road to practical application. The current status of such ideas for turbulence modification has been examined in previous AIAA meetings (Bushnell 1983; Corke *et al* 1982). We will therefore not go over the ground that has already been covered by our predecessors but concentrate on what seems still to be the most intriguing possibility in all of these, namely that of being able to modify turbulence favourably by the use of so-called manipulators. (These have also been called large eddy break-up devices, but this name presumes a mechanism that does not yet seem to have been conclusively established.) The notation for such manipulators is shown in figure 1.

2. General approach

One of the major objectives of the present analysis is to delineate the conditions under which a turbulent boundary layer manipulated by the insertion of a passive object may lead to a lower overall drag than in the unmanipulated flow.

First of all, it must be remarked that almost any object or device inserted in the boundary layer will lead to lower *friction* drag (– we shall present the evidence for this shortly): the question is whether the lower friction is not more than lost by the 'parasite' drag of the device itself. Let us consider the data available on such flows (often not studied in the context of drag reduction at all). We may begin with the experiments of Klebanoff & Diehl (1951), who measured boundary layer development with a rod placed on the surface. Figure 2 shows the growth of the momentum thickness θ with and without the rod. It is seen that with the rod θ is always higher (implying higher total drag) but that there is a short region downstream of the rod where θ goes down. It is possible that the friction here is not only reduced but is actually negative due to local separation. It is convenient to think of such flows as representing *wall-wakes* (as we shall call them), in which momentum is extracted from a wall-bounded flow; this is in contrast to *wall-jets* where momentum is injected into the flow, usually through a nozzle at or below the surface.

Wall-wake flows need not necessarily result only from the placement of objects *on* the surface. Marumo *et al* (1978) have reported studies with an 8 mm dia rod at heights of 0.222, 0.556 and 1.24 times the undisturbed boundary layer thickness δ_m ($\simeq$ 27 mm). Their results, shown in figure 3, once again demonstrate how in general the skin friction coefficient drops when the rod is inserted.

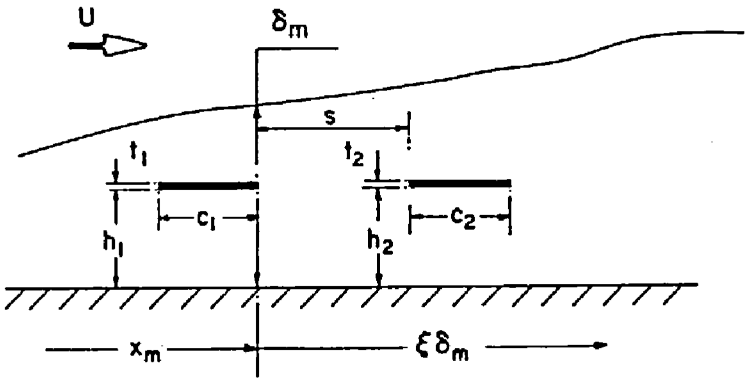

Figure 1. Sketch of a tandem blade manipulator, showing notation adopted here. One or both the blades of the manipulator could be at some small angle of attack.

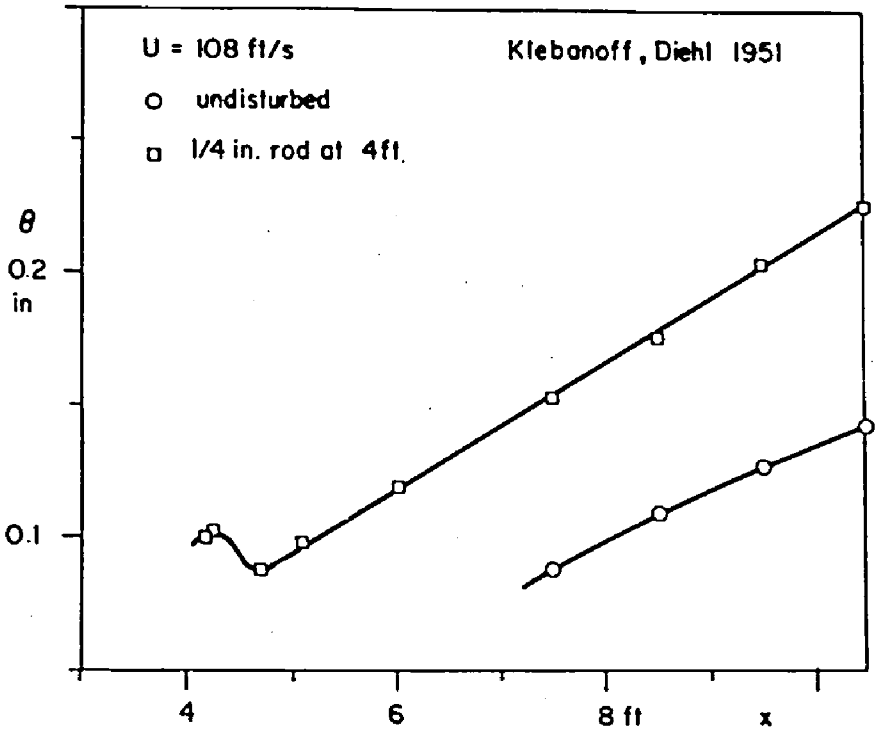

Figure 2. Effect of a rod placed on the wall on the growth of the boundary layer momentum thickness: data from Klebanoff & Diehl (1951).

We conclude by citing just one more example, from the work of Kacker & Whitelaw (1971). Actually the flow studied by them was a wall-jet, but the lip of the nozzle, which rested above the surface, acted like a wake generator: when the jet was slower than the free stream (a situation that they also describe as a wall-wake), the skin friction coefficient showed a substantial drop (figure 4).

Now the insertion of any object in the flow is bound to produce a wake of some kind, and a corresponding *increment* in drag. However, especially if the streamwise extent of the body is not small, the new surface introduces an additional boundary

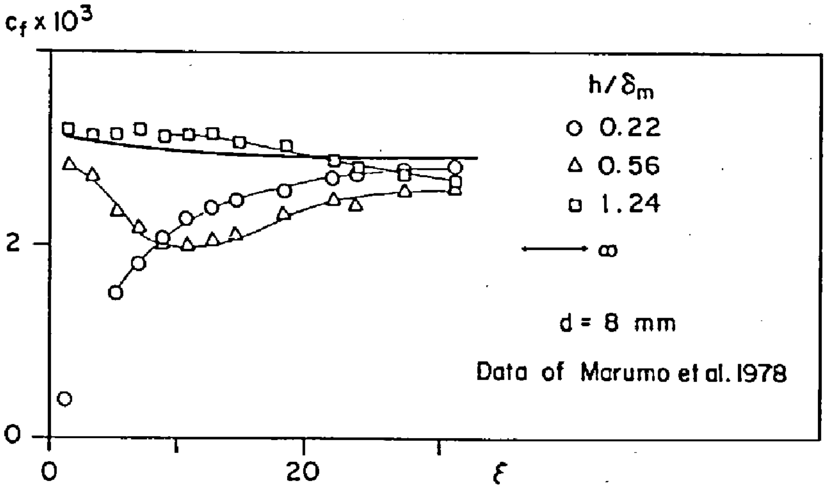

Figure 3. Streamwise variation of skin friction coefficient with a rod placed in a turbulent boundary layer at different heights above the surface: data from Marumo *et al* (1978). Full line indicates undisturbed boundary layer.

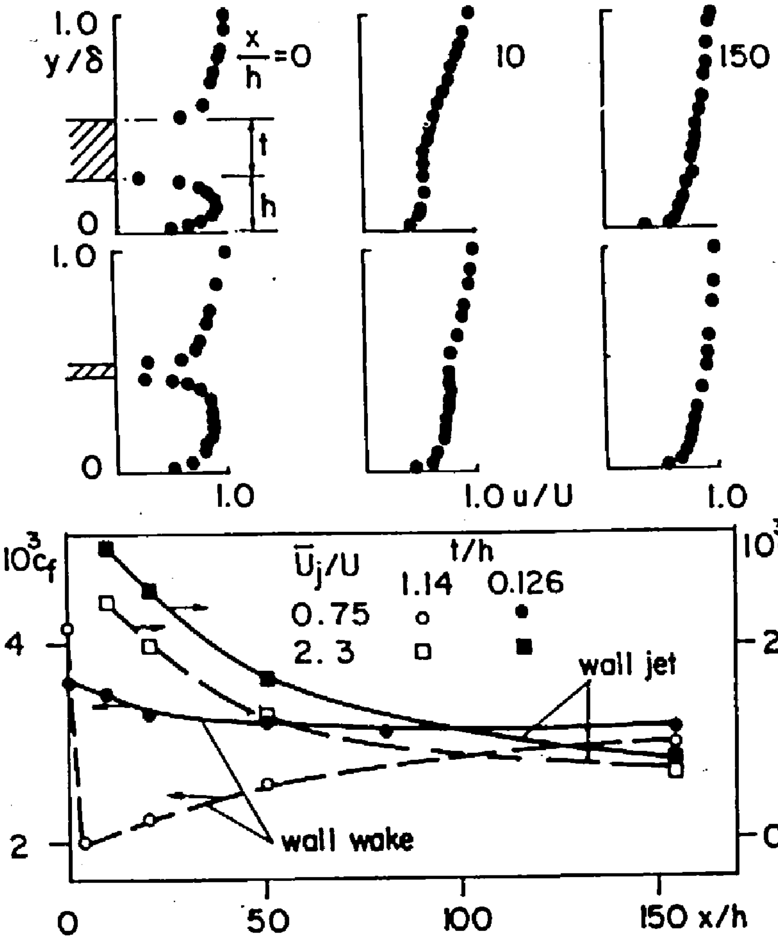

Figure 4. Data from Kacker & Whitelaw (1971) on velocity profiles and skin friction coefficient in a wall-jet and a wall-wake, the latter being defined by the condition that $\bar{U}_j/U < 1$ where $\bar{U}_j$ is the average jet velocity and U is the velocity at the edge of the boundary layer. The velocity profiles in two wall-wake cases are shown in the upper part of the figure. Note the large drop in skin friction in the thick-plate case.

in the flow; all flow velocities are forced to vanish over this boundary, and (if the object is impervious) a discontinuity in the instantaneous pressure can be sustained across the surface. The intriguing question is whether the enforcement of such boundary conditions can have a sufficiently large beneficial effect on the turbulent flow so that the drag penalty of the device itself can be overcome.

In the light of these observations, it is convenient to distinguish between what we shall call here the *wake* effect (loss of momentum in the main flow) and the *blade* effect (establishment of new boundary conditions in the main flow) – fully realizing, of course, that the two will generally coexist (to different degrees) with any particular device.

3. The wake effect

All experiments with wakes interacting with boundary layers show that even the strong disturbances introduced by sizeable bodies eventually die down, at rates that increase as the body approaches the surface. Clauser (1956) reported decay distances (the precise definition he used is not clear) of 2 δ_m and 8 δ_m for the mean velocity perturbation produced by a 1/2 in. rod when placed at heights of $0.16\delta_m$ and $0.59\delta_m$ respectively from the surface.

A wake in uniform flow is characterized largely by its momentum thickness θ_w: although initial conditions, including in particular the geometry of the body producing the wake, can exert a long influence on flow development, there is much evidence that, sufficiently far downstream, it is useful to adopt θ_w as a basic length scale in the flow (Sreenivasan 1982). In this spirit we examine the wake effect of boundary layer manipulators.

Figure 5 shows the variation of the velocity defect with streamwise distance for a rod immersed in the boundary layer. It is seen that for distances of order $200\theta_w$, the variation follows the inverse square root law characteristic of equilibrium wakes. At larger distances, however, the velocity deficit seems to fall off more rapidly – an effect that was noted by Eskinazi (1959), who also suggested the explanation that energy transport is helped considerably by the prevailing velocity gradients outside the wake, especially on its wallward edge. (Actually Eskinazi suggested an average variation of the maximum defect velocity like $x^{-4/5}$, but his data are not inconsistent with the view we would take that it is only for $x/\theta_w \gtrsim 200$ that the decay is faster: closer to the body the wake is thin enough that mean flow shear does not have a significant effect.)

Figure 6 shows Eskinazi's data on wake thickness; this again grows at first like $x^{1/2}$ as in the equilibrium solution, and much faster downstream – a trend that is consistent with the observed variation of the velocity deficit.

The most extensive study of such wall-wakes to-date is due to Marumo *et al* (1978), whose work we have already cited in §2 (see figure 3). Their skin friction coefficient, estimated using a Preston tube (in reasonable agreement with the Ludwieg-Tillmann formula) shows that with the rod close to the wall, there is a substantial reduction in skin friction, almost certainly associated with a separation bubble just downstream of the cylinder. At the highest rod position ($1.24\ \delta_m$) c_f starts dropping only at 400 mm = 15 δ_m downstream of the rod. At the intermediate position ($0.556\ \delta_m$) c_f reaches a minimum around 11 δ_m, and has relaxed half-way to the asymptotic value far downstream at about 7 δ_m further downstream. Interestingly, the recovery distance at the lowest cylinder position is seen to be about the same, measured in this case from around where $c_f = 0$.

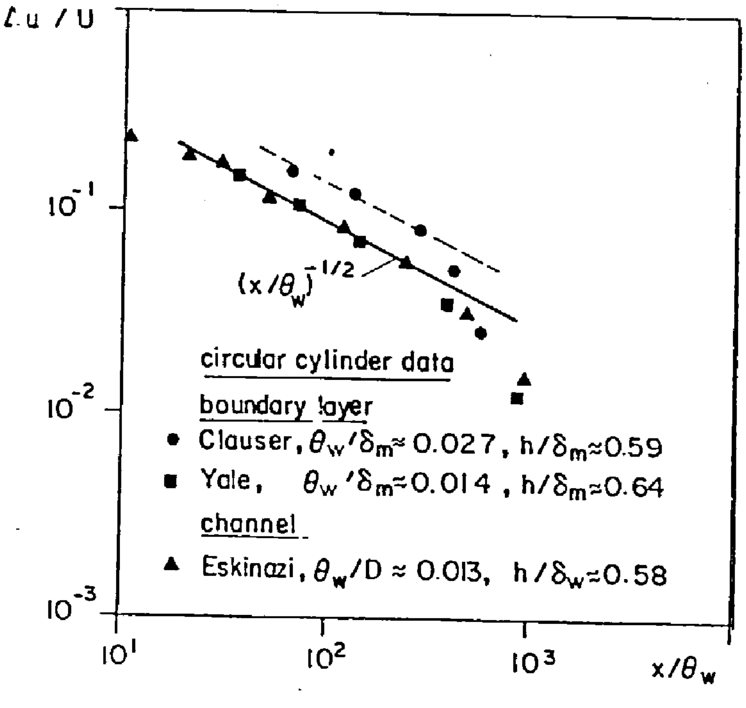

Figure 5. Velocity deficit due to insertion of circular cylinder in a turbulent boundary layer. The Yale data are from Lynn & Sreenivasan (1984, unpublished).

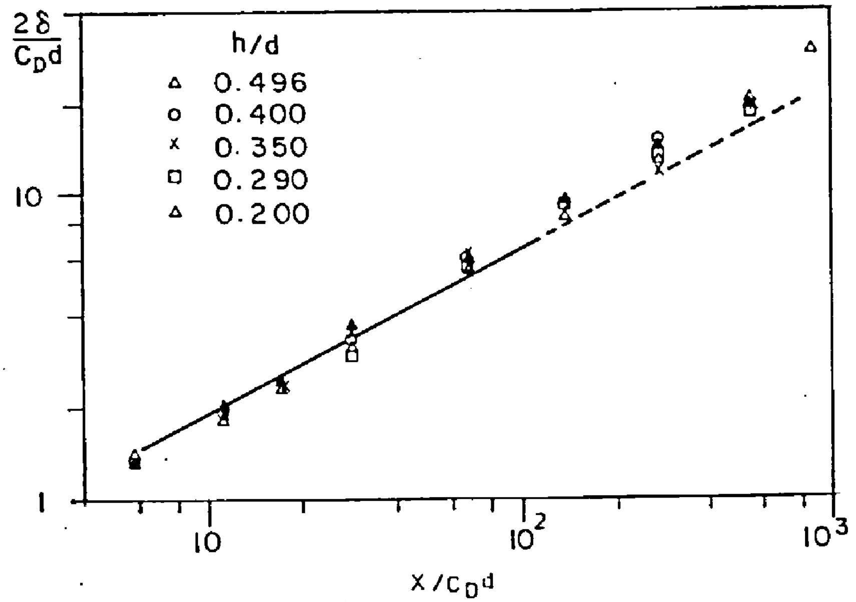

Figure 6. Half-defect thickness of wake generated by cylinder in a turbulent boundary layer, $\eta = h$ (data from Eskinazi 1959).

Greater insight into the structure of this flow is perhaps gained by examining the measured turbulence length scales, which are summarized in figure 7. The cylinder introduces smaller scales into the flow, in part through Karman vortices (for which there was independent evidence in the measured periodicity of the correlation coefficients), albeit with an altered shedding frequency when the cylinder is close to the wall. The data for the intermediate cylinder position show that at $\xi = 6.9$ the scales are still rather low, like those in a wake; but at $\xi = 14.3$ they have recovered to boundary-layer-like values. For the high position, the scales are hardly affected by the wake up to $y = 10$ mm, but are clearly lowered further away. At the low position, the scales at $\xi = 1.4$ are almost the same as in the wake.

A key length scale in these phenomena seems to be provided by the distance, say x_w, to the station around which the wake begins to impinge directly on the plate. Although no precise value for this length can be determined from the experimental data, it seems plausible (from an examination of the measured skin friction) that c_f begins to recover downstream of that point. For example, in the intermediate position, c_f recovery starts around $\xi = 10$; the scales at the wall are wake-like at $\xi = 6.9$, and boundary-layer-like at $\xi = 14.3$. The other two sets of data are also consistent with the proposal that wake-impingement signals c_f recovery. More recent data of Lynn (1987) on half-defect trajectories confirm this general expectation.

Recovery distances from minimum c_f are slightly less than 10 δ_m. Taking the wake thickness δ_w to be proportional to $(\xi\delta_m\theta_w)^{1/2}$, it is seen that δ_w becomes comparable to h in a distance

$$x_w = \text{const.}(h^2/\theta_w)$$

from the manipulator.

The early work of Yajnik & Acharya (1977) showed skin friction reduction when a screen was introduced in the boundary layer; from the general discussion above,

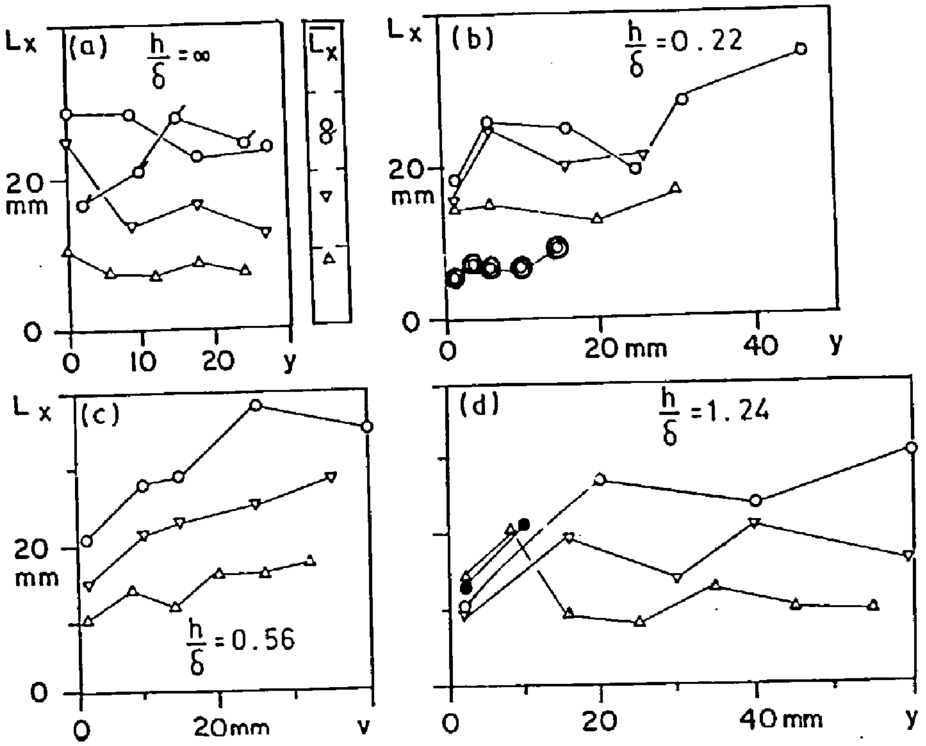

Figure 7. Distribution of integral length scales in a turbulent boundary layer with cylinder placed at different heights (after Marumo *et al* 1978). (a) shows the scales in a free wake and in the undisturbed boundary layer (flagged circles). $\overline{L}_x$ is the length scale averaged over the outer region of the boundary layer. The double circles in (b) are points that we infer from the test to correspond to $\xi = 1.4$ (they appear to have been wrongly marked in the original).

Symbols: $\xi =$ ● 1.4, △ 6.9, ▽ 14.3, ○ 31.

we believe that the flow in these experiments was in the nature of a wall-wake, but because the wake generator is wide and dispersed the length x_w is not easily defined in this case; the long recovery distances (of order $45\delta_m$) reported here may be due to the wide range of h characterizing the wake generator.

4. The blade effect

Considerable evidence has accumulated during the last five years that even without a strong wake effect there can be a substantial reduction in the skin friction co-efficient when an aerofoil-like body (we shall call them "blades", hacking away at the eddies if you wish: also often called ribbons and plates) is immersed in the turbulent boundary layer. We may consider, for example, the data of Mumford & Savill (1984), shown in figure 8, based on wall stress measurements using a direct skin friction balance. What is interesting here is that the reduction in skin friction coefficient, at the station $\xi = 12.5$, is of the same order with a flat plate aerofoil whose chord is of order δ_m, as with a rod of diameter $0.08\ \delta_m$. It is clear therefore that a body which has a much smaller momentum thickness can for other reasons induce the same kind of skin friction reduction as a wall-wake.

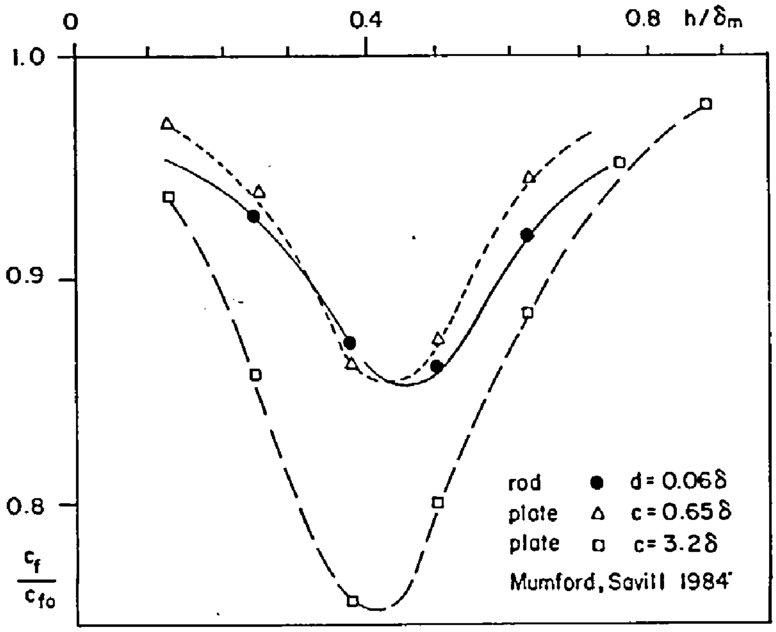

Figure 8. Skin friction at a fixed station ($\xi = 12.5$), as a fraction of undisturbed value, with rod and blade placed at different heights above the surface (Mumford & Savill 1984).

The question here is the relative magnitude of the drag of the two kinds of bodies we are discussing. This has generally been sought to be resolved by making measurements of the momentum thickness. Typical results from the work of Nagib and co-workers (Corke *et al* 1979) are shown in figure 9; it is seen that just downstream of the blade there is a jump in the momentum thickness (attributable to blade drag), but further downstream the growth in thickness is slower than it would have been in the absence of the blade, implying lower skin friction. In particular, there is a station downstream beyond which the momentum thickness of the boundary layer is actually less than it would have otherwise been, implying favourable interference and a corresponding reduction in the *total* drag of the surface-blade combination. Although such data tend to be slightly marred by the difficulty of ensuring strict two-dimensionality, evidence from a variety of measurements in different laboratories tend to show that beyond a certain point there could be a small net reduction in the drag experienced by the surface. Figure 10 summarizes these data, in terms of a drag index, showing that beyond 50 boundary layer thicknesses, if not earlier in certain cases, the drag is marginally lower.

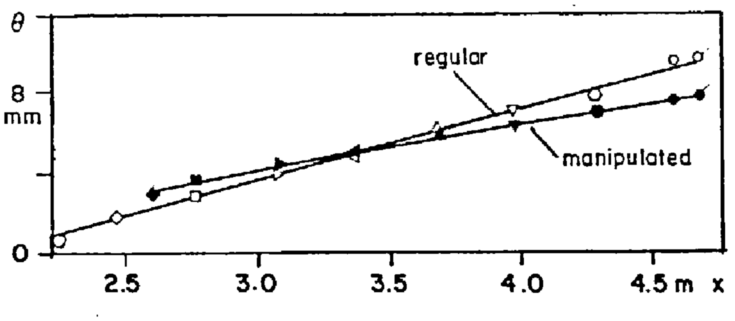

Figure 9. Variation of momentum thickness in manipulated boundary layer.

If we note that drag reduction estimates based solely on two-dimensional momentum balance are often unreliable (because of the invariably present small three-dimensionalities in small-to-moderate aspect ratio wind tunnels), the drag balance required to arrive at the conclusion of the sort shown in figure 10 requires an accurate estimate of both the surface friction of the flat plate and the device drag. From a detailed assessment of the accuracy of these various measurements (Lynn 1987), it appears that the net drag reduction, if it occurs, is quite small (no more than a few per cent), and that its realization in practice is somewhat uncertain. We may also note the recent experiments on the effect of blade manipulators in turbulent channel flow, reported by Prabhu *et al* (1987). In these experiments all combinations of manipulators tried, including tandems and stacks, showed no reduction in the pressure loss for a given mass flow through the channel. Although it may be questioned whether channel flow results are directly applicable to boundary layers, the great similarity in the turbulent structure of the two flows suggests that the negative result in the channels would be very hard to reconcile with a large effect in boundary layers.

It must be emphasized that we cannot assert, on the basis of the measurements reported as they stand, that the wake effect of the blade makes no contribution to skin friction reduction. To illustrate this point, we plot in figure 11 the velocity defect as a function of distance from the manipulator in the case of tandem blade manipulators. Once again, a variety of measurements here show that up to about a couple of hundred momentum thicknesses the observed velocity defect in the blade manipulator wakes scales the same way as in a cylinder wake in a uniform stream. However, the wake of a blade manipulator does not spread in quite the same way as that of a cylinder. Figure 12 shows data on the edge of the wake, both wallward and outward, from some measurements made at Yale (T B Lynn & K R Sreenivasan 1984, unpublished) using a blade manipulator located half-way across the boundary layer. The striking result here, in comparison with the wall wakes discussed in § 3, is that the wallward edge of the wake appears to impinge on the wall much sooner. It also appears that the manipulated boundary layer is slightly *thicker* very close to the manipulator, followed by a reduction in thickness almost immediately further downstream. Figure 13 shows the measured position of both edges of the wake when the manipulator is at negative incidence compared with the

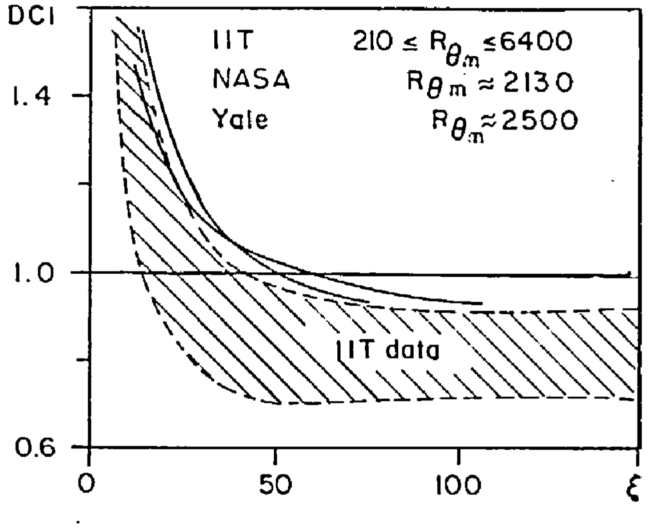

Figure 10. Summary of data on a drag change index, defined as the ratio of the drag measured from a reference station in the manipulated boundary layer to that in the unmanipulated boundary layer. The IIT (Illinois Inst. Technol.) data are from Corke *et al* (1982), the NASA data from Hefner *et al* (1983), and the Yale data from Lynn & Sreenivasan (1985).

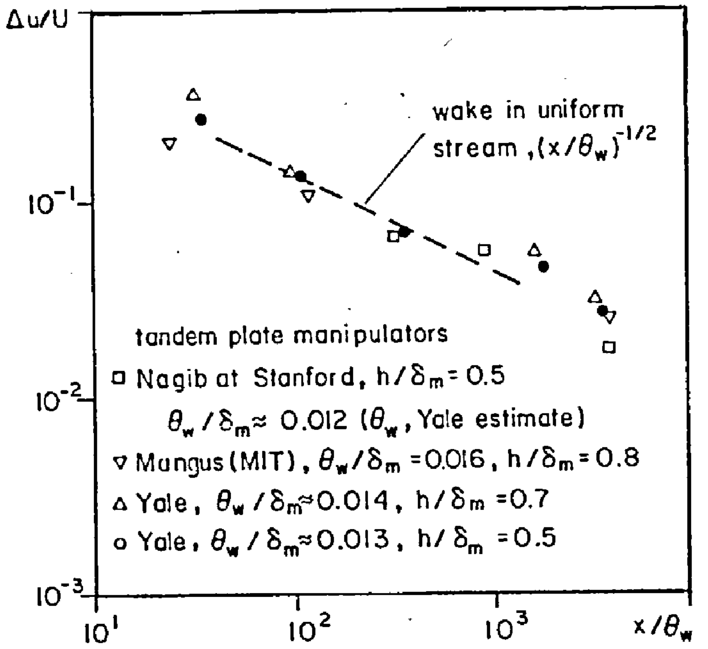

Figure 11. Wake defect velocity in manipulated boundary layers. The Yale data are from the unpublished measurements of Lynn & Sreenivasan (1984); the MIT data from Mangus (1984).

same parameters at zero incidence. It is seen that the outward edge of the boundary layer is further lifted at the negative incidence; however, the wallward edge of the wake does not show any significant change.

We finally look at the evidence on the velocity defect in the wake of a tandem plate manipulator, deduced from measurements reported by Nagib (Appendix B of Corke *et al* 1979). These data, shown in figure 14, indicate that the character of the wake quickly undergoes a change in this case, let us say around 10 boundary layer thicknesses downstream of the second manipulator. Beyond this point, for example at $\xi = 45$, no wakelike profile or defect is evident. A small positive angle of attack on the manipulator appears to produce an appreciable increase in the drag reduction (figure 15), as is made clear from the measurements of Plesniak & Nagib (1985).

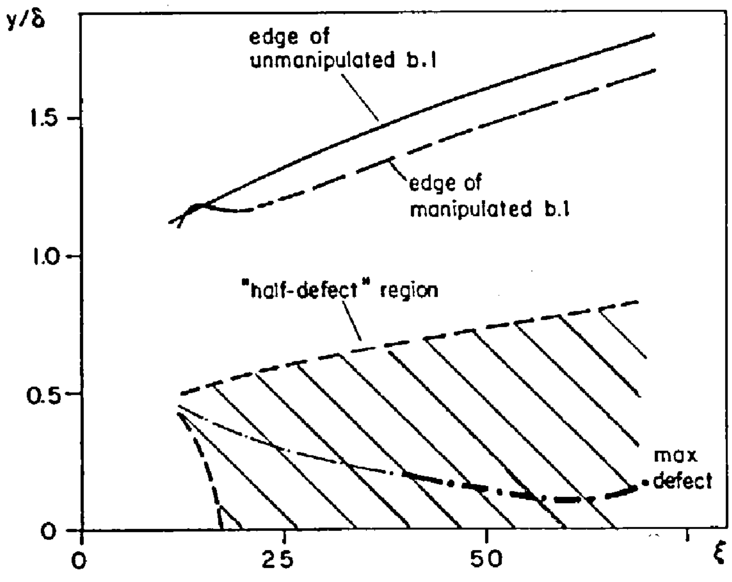

Figure 12. Spread of manipulator wake in boundary layer, from the measurements of Lynn & Sreenivasan (1984, unpublished).

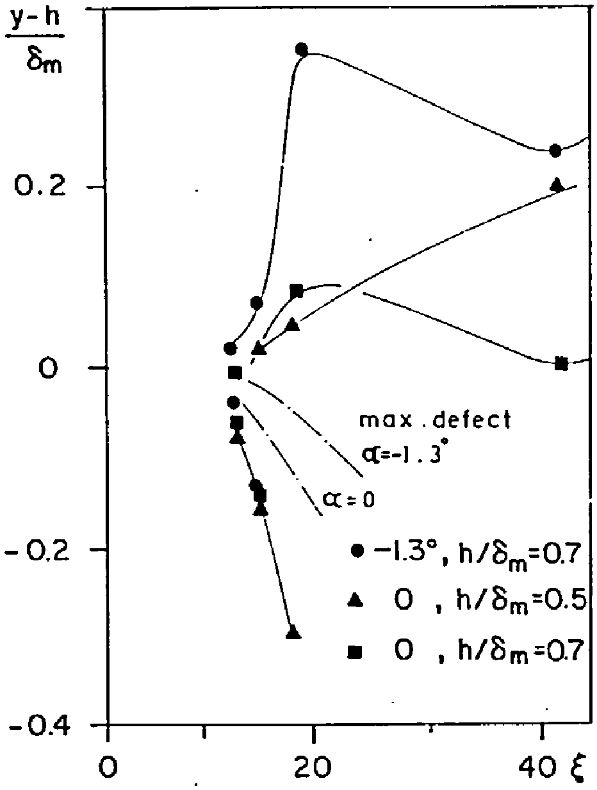

Figure 13. Effect of manipulator incidence on wake edges in manipulated boundary layer.

These observations, taken together, suggest that there is a separate effect, which we shall call the blade effect, that is responsible for the different behaviour characteristic of blade manipulators as distinct from the wall-wake results of § 3.

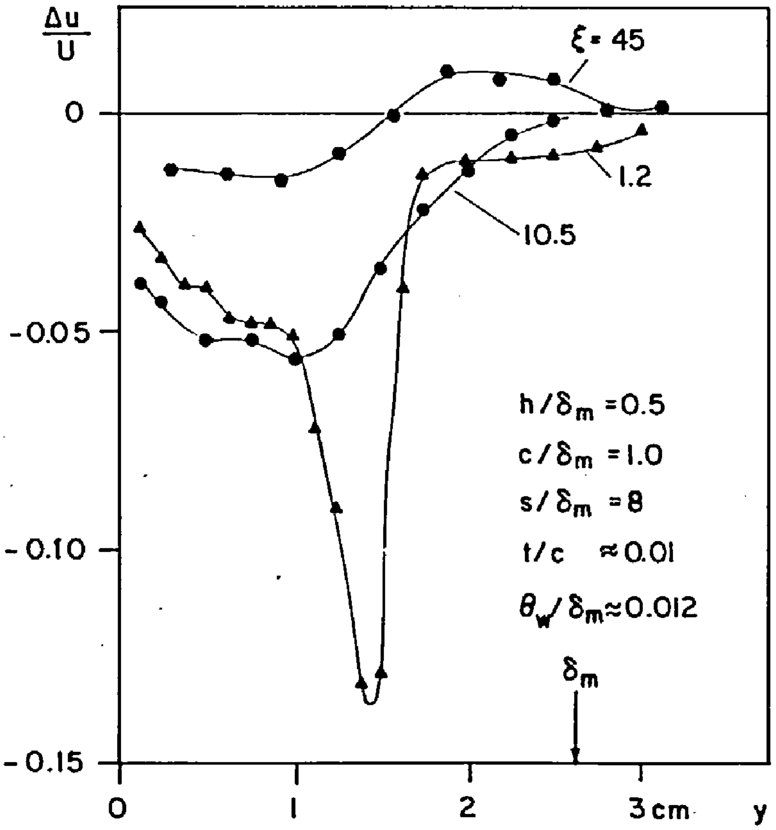

Figure 14. Defect profiles in manipulated boundary layer.

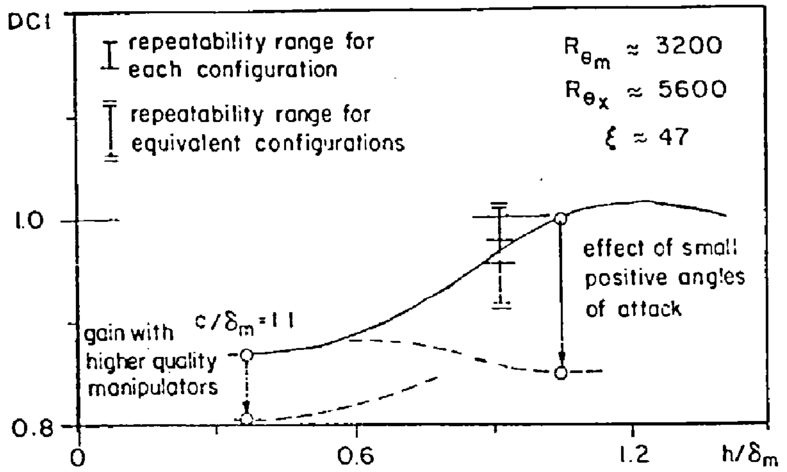

Figure 15. Effect of blade incidence on drag change (from Plesniak & Nagib 1985).

This is particularly shown up in figure 16 where the inclination of the stream just behind the manipulator, as measured by Plesniak & Nagib (1985), is seen to be appreciably different from values further downstream.

5. Discussion

Table 1 makes a broad comparison of the wake and blade effects discussed above. We now make the hypothesis that while the wake effect may be expected on general grounds to scale on the momentum thickness of the wake, the blade effect is more likely to scale on the chord c of the blade (at zero incidence: otherwise the incidence would be an additional parameter). It is attractive to speculate that while the wake effect is due to the drag of the body the blade effect is primarily due to the lift on it. An analysis of the lift on aerofoils immersed in boundary layers, made by Kumar & Narasimha (1986), shows that the major contribution to the lift at zero incidence comes from the presence of shear in the approaching stream. We conjecture that the lift so experienced by the body leads to an induced velocity downstream of the blade which is such that the coherent structure in the boundary layer is favourably modified from the point of view of the drag experienced by the surface. We have earlier remarked (Narasimha & Sreenivasan 1979) that the turbulent boundary layer appears to be particularly sensitive to manipulation with the normal velocity component in the flow. It would not be surprising therefore if

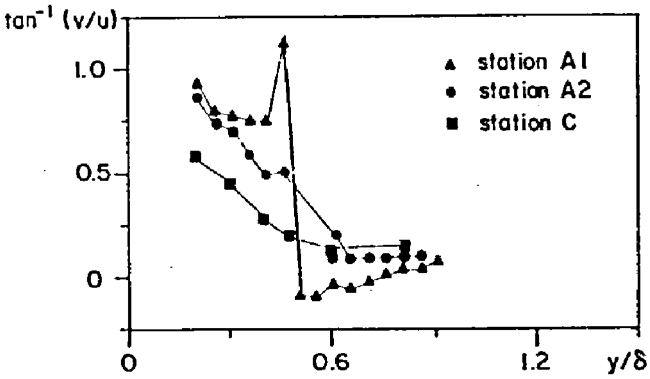

Figure 16. Mean streamline inclination in manipulated boundary layer (Guezennec & Nagib 1985).

Table 1. Blade and wake effects compared.

Manipulation	
Wake effect	Blade effect
* Alters turbulent energy production * Introduces smaller scales * Generates Karman-type vortices	* Suppresses normal velocity over blade * Generates Kutta-Joukowsky-type vortices * Alters structure of turbulence
Scales on θ_w, h Limit: $c/\delta \rightarrow 0$ θ_w/δ finite	Scales on c, h Limit: $\theta_w/\delta \rightarrow 0$ c/δ finite

the downward velocity field induced by the lift on the blade (i.e. by the vortex responsible for it) so alters the normal velocity component in the turbulent flow that the balance maintained in an equilibrium turbulent boundary layer is upset, resulting in a reduction in the skin friction as well as the net drag. We know from experience in other situations that such effects can persist for long distances, because of flow-memory.

These arguments suggest that a useful map of the effect of a manipulator in a boundary layer would be in the plane of the two non-dimensional variables θ_w/δ_m and c/δ_m. All available results on drag coefficient are plotted on this map in figure 17. If the chord of the body is negligible, as it would be in the case of a circular cylinder immersed in the flow, we have the wake effect, characterized by the ordinate in this plane. An ideal manipulator would have zero drag and so would be represented by the abscissa. Of course such ideal manipulators do not exist (although it is interesting to speculate on the possibility of reducing the drag of the manipulator, for example by setting it in motion), but it is clear that there is a certain region in figure 17 where we may expect a drag reduction. This boundary corresponds to the line $c/\theta_w \simeq 40$. The fact that most measurements are not too far from this boundary may explain why experimental work in this area is so hard and also why the reported drag reductions have not always been beyond the likely bands of uncertainty in the measurement technique. Looking at this diagram, the scatter in the different results reported so far is no longer very surprising.

The reason for the fairly large manipulator chord (in terms of θ_w) necessary for favourable interference is not hard to see from another point of view. Lynn (1987) concluded from a detailed study of iso-correlation maps of the velocity field that one effect of the blades (as already pointed out at the beginning of § 4) appears to be to cut the hairpin eddies present in the boundary layer into two parts; the efficiency of this operation being directly dependent on the chordwise extent of the blades. The remnants of the hairpin eddies on the top of the blade are now inclined to the flow direction at much shallower angles than 45°, thus making them inefficient at entraining the outside flow. Because the rate of strain is very small in the outer region of the turbulent boundary layer, it takes a large distance for the equilibrium structure to be restored. This accounts for the relatively large relaxation distances observed behind blades.

We end by noting one paradoxical feature that *ought* to be observed in manipulated flows but is not supported by any strong direct evidence yet. This is as

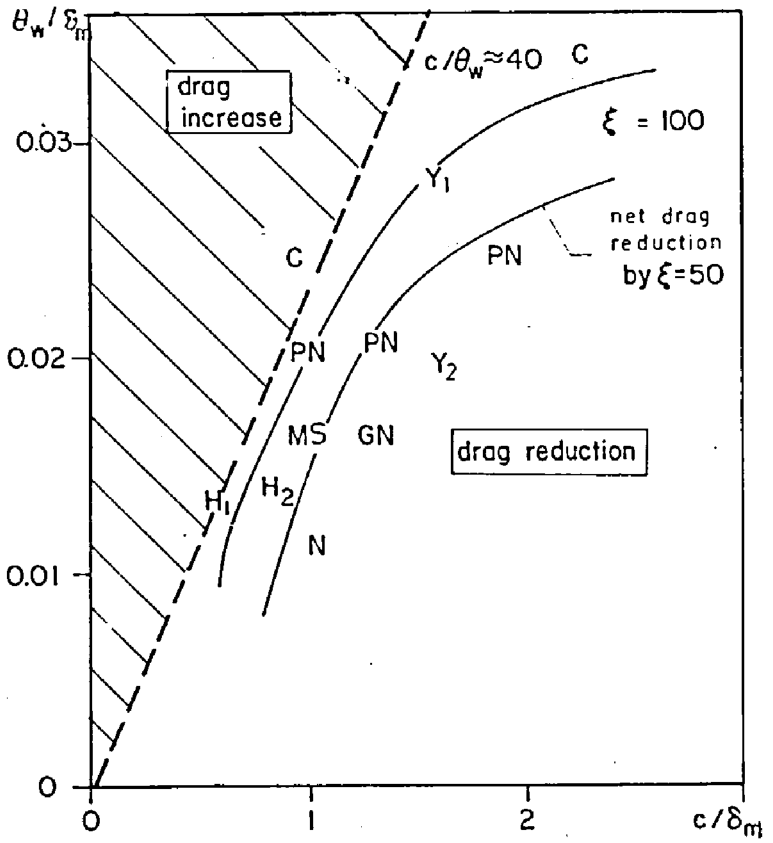

Figure 17. Tentative map of drag reduction regime in variables characterizing respectively the wake and blade effects. A blunt body like a circular cylinder would plot very close to the y-axis.

C: Corke *et al* (1979); H_1, H_2: Hefner *et al* (1983); MS: Mumford & Savill (1984); PN: Plesniak & Nagib (1985); Y_1, Y_2: Lynn & Sreenivasan (1985); N: Corke *et al* (1982); GN: Guezennec & Nagib (1985). MS, H_1, and the two C's do not report any net reduction in drag at one last station of measurement. Y_1 reports no drag reduction at $\xi = 70$, but extrapolated to $\xi = 100$, a small reduction seems possible.

follows. Suppose the manipulator is effective and does lead to a net decrease in the boundary-layer momentum thickness downstream as shown in figure 9. Now we expect on general grounds (see e.g. Working Rule No. 4, Narasimha 1984) that, sufficiently far downstream, the manipulated boundary layer asymptotically returns to "maturity" or "equilibrium" in some sense. If now in this state the momentum thickness Reynolds number is lower than it would have been at the same station in the unmanipulated boundary layer – as it must be for net drag reduction – the skin friction coefficient should be higher at that station. Thus the traditional wisdom on the behaviour of the boundary layers – namely that irrespective of the perturbation made there will be a tendency for the boundary layer to return to the usual equilibrium sufficiently far downstream of the perturbation – implies that an *increase* in skin friction coefficient far downstream is inevitable. If this is true it further follows that any possible reduction of drag due to the insertion of a manipulator will be achieved only for limited downstream lengths behind the manipulator where the blade effect has temporarily won over the wake effect. Precisely what this distance is we still do not know, and we find it difficult to estimate it from currently available measurements. We believe however that the resolution of this paradox will go far towards elucidating the effect of manipulators on boundary layers.

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