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The effect of wind-tunnel screens on nominally two-dimensional boundary layers

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Spanwise variations of surface shear stress, amounting to 10 % or more, may be produced in nominally two-dimensional boundary layers by a spatial instability of the flow through the wind-tunnel damping screens: boundary layers are shown theoretically to be very sensitive to variations of free-stream direction. Screens with open-area ratios more than about 0·57 do not produce appreciable spanwise variations in the boundary layer, and it is recommended that tunnels for boundary-layer measurements should be fitted with such screens. The critical open-area ratio does not seem to depend noticeably on Reynolds number in the usual range encountered in wind tunnels, but the figure of 0·57 should not be taken as general until measurements have been made in a representative selection of wind tunnels in other laboratories.

1. Introduction

Klebanoff & Tidstrom (1959), Favre & Gaviglio (1960) and Head & Rechenberg (1962) have observed large, quasi-periodic spanwise variations of the thickness and surface shear stress of boundary layers in the working sections of wind tunnels fitted with screens in the settling chamber. Fernholz (1962) has investigated the variations in a turbulent boundary layer in some detail on the assumption that they originate in the transition region; his results show that the percentage variation in surface shear stress increases with distance from the leading edge, but it is shown below that this need not be related to transition.

These variations have also been observed in the N.P.L. boundary-layer tunnel, and, since they were unacceptably large, a cure was sought. This report presents the results of the investigation, which was carried far enough to indicate the cause and the cure, but no direct measurement has been made of the way in which the variations arise. Such measurements would, as it happens, be very difficult and it is sufficient for the present purpose to outline the most probable course of events and to propose a rule for ensuring that the variations do not occur. This rule is found to be simply a lower limit on the open-area ratio of the damping screens.

In §2 it is shown that the surface-shear-stress variations are effectively locked to the last screen in the settling chamber, and that the property of the screen which determines the pattern is simply the local open-area ratio. Since it is improbable that variations of the U-component of the free-stream velocity could cause the observed boundary-layer behaviour, the effect of variations in free-stream direction is examined in §3 and is shown to be extremely large (this effect has also been investigated by Crow (1964)). In §4, the production of such directional variations by the screens themselves is discussed. The assumption that the mechanism is the spatial instability of the multiple jets emerging from the pores of the screen, described by Morgan (1960), is confirmed by the finding that screens with an open-area ratio greater than about 0·57 do not produce shear-stress variations, which agrees with the stability limit mentioned by Morgan. It is suggested that wind tunnels should be fitted with screens with an open-area ratio not less than 0·57, corresponding to a pressure-drop coefficient of about 1·6 at 12 ft./sec. Since the shear stress variations grow linearly with distance from the leading-edge they are not appreciable on aerofoils of small chord such as three-dimensional aircraft models and it is probably unnecessary to modify tunnels used *only* for this sort of work. If the tunnel turbulence is high, or the settling chamber very long, the pattern may wander from side to side sufficiently to be unnoticeable in the mean.

A shortened account of the work reported in this paper has already been published by Bradshaw (1964).

2. The correspondence between screen orientation and surface-shear-stress variations

Figure 1 shows the settling chamber of the N.P.L. boundary-layer tunnel (Bradshaw & Hellens 1964). As seen, the first two screens downstream of the honeycomb are clamped in curved frames to reduce tension in the wires due to

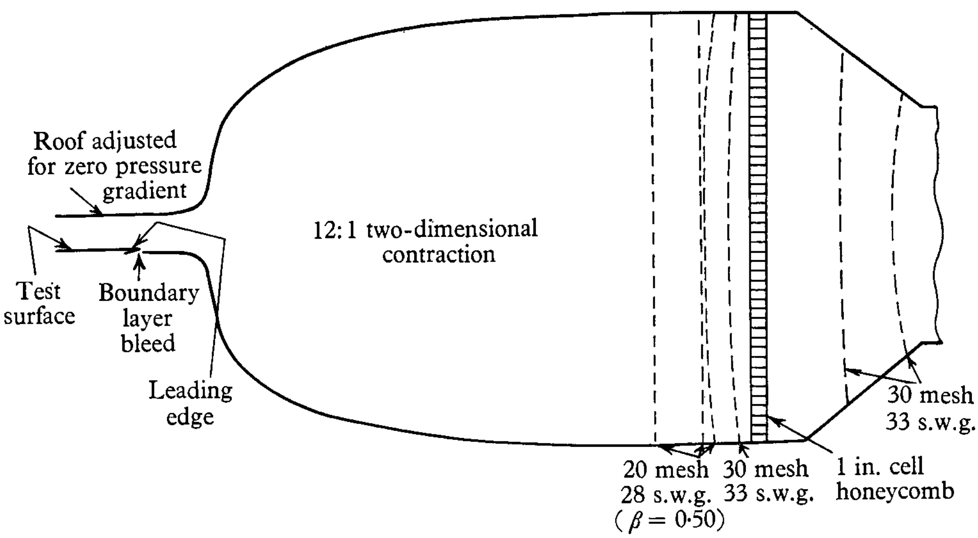

FIGURE 1. Boundary-layer tunnel screen arrangement.

air loads. They are therefore slightly wrinkled, while the two downstream screens, which were added at a time when it was believed that wrinkles were the chief cause of the spanwise variations observed in the tunnel, are clamped between flat frames and are admirably free from wrinkles.

Figure 2 shows the variations of surface shear stress across part of the floor of the working section 65 in. from the leading edge (at which the contraction boundary layer is removed), at a Reynolds number

$$U_1x/\nu = 4{\cdot}2 \times 10^6 \,(U_1 \simeq 130\,\text{ft./sec});$$

the boundary-layer thickness was about 1 in. The pattern was unaltered when the 32 s.w.g. (0·011 in. diameter) trip wire, attached with 0·007 in. 'Scotch tape' about 1 in. from the leading edge, was replaced by a much larger one (22 s.w.g., 0·028 in. diameter). No measurement was made with free transition, because one would then expect spanwise variations to occur as a result of variations in transition position due to excrescences and other small disturbances, quite irrespective of the state of the screens.

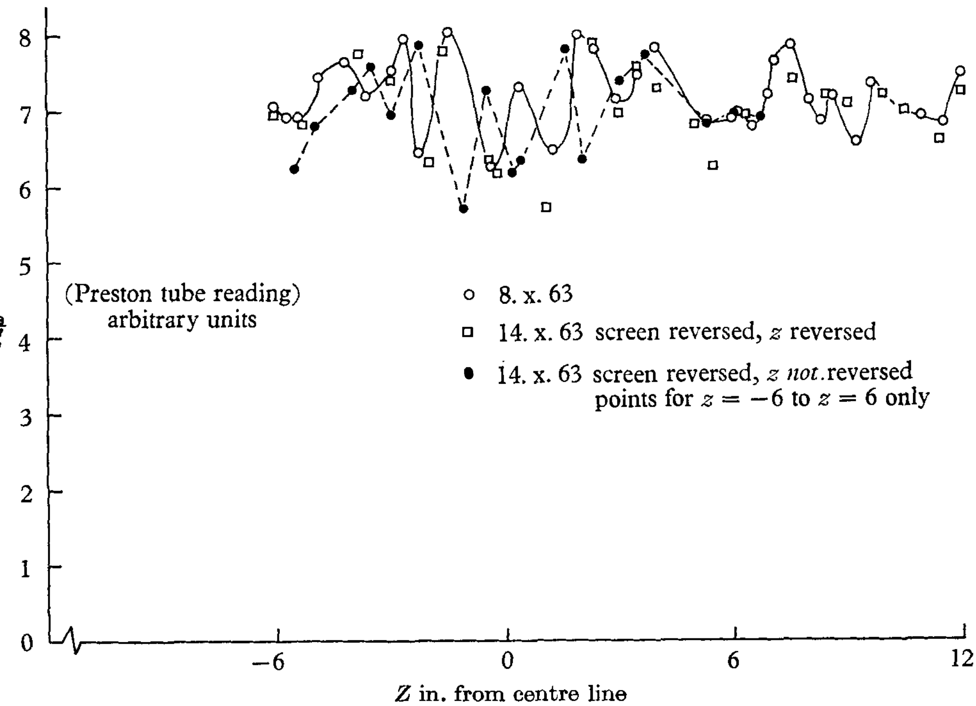

FIGURE 2. $c_f(z)$ in boundary-layer tunnel with 20-mesh 28 s.w.g. screens (β = 0·50): x = 65 in., $U_1x/\nu = 4{\cdot}2 \times 10^6$.

Also shown in figure 2 is the surface-shear-stress pattern obtained when the last screen was turned left to right. It is seen that the pattern has changed; there is a large difference between the original run (circles) and the run with screen reversed (solid dots, $-6 < z < 6$ only). There is very little difference, however, between the original run and the run with screen reversed if the latter is plotted with the sign of z also reversed (squares). Therefore, the surface-shear-stress pattern is effectively locked to the last screen and must be determined by the properties of the last screen. Variation in mesh size, due to poor weaving or dirt accretion, and wrinkles are the most obvious possibilities, but the above results immediately show that wrinkles are not responsible because the pattern does not depend on the direction of flow through the screen.† (This conclusion had been tentatively reached as soon as it was apparent that the great care taken to keep the last screen free of wrinkles had not reduced the shear-stress variations.) The only aerodynamic property of the screen that is independent of the direction of the air flow is the open-area ratio, and we therefore conclude that the spanwise variations in the boundary layer are caused, directly or indirectly, by variations in the open-area ratio of the screens.

The chief direct result of variations in open-area ratio is a corresponding variation of the U-component of velocity. However, it is most unlikely that such a variation would have a noticeable affect in the working section of a tunnel with a contraction of the usual area ratio; the variation of velocity downstream of the screens of the boundary layer tunnel was about $\pm 2\,\%$, about the same as the variation of open-area ratio measured on another sample of the same screen material, and the variation in the working section would be 1/144 of this, the contraction ratio being 12. The corresponding percentage variations of surface shear stress in a *laminar* boundary layer are unlikely to be more than 1·5 times the percentage variation of velocity, since $\tau_w/\frac{1}{2}\rho U_1^2 \propto (Ux/\nu)^{-\frac{1}{2}}$ and restoring viscous stresses would be set up. There is no evidence that a *turbulent* boundary layer is any more sensitive and the variations observed by Klebanoff & Tidstrom (1959) in a laminar layer are of the same order of magnitude as those observed by other workers in turbulent layers.

We must therefore seek another explanation. It will be seen below that the variations in open-area ratio act as triggers for a spatial (*not* temporal) instability of the flow through the pores of the screen, which may be expected to lead to appreciable variations of stream *direction*. First, we consider the effect of variations in free-stream direction on the flow in the boundary layer, and then consider the instability phenomenon and methods of eliminating it.

3. Effect of W-component periodicity on a boundary layer

The original version of this paper (Bradshaw 1963) contains an approximate analysis of the effect of a lateral velocity component $W_1 = W_{10}\cos\alpha z$ on a boundary layer in zero longitudinal pressure gradient. The major result is that the boundary-layer thickness is $\bar{\delta}(1+s_1\sin\alpha z)$ where

$$s_1 = \alpha\frac{W_{10}}{U_1}\frac{x}{2}$$

if s_1 is fairly small. Crow (1964) has now derived this result more rigorously and has also shown that the inclusion of viscous restoring forces in the analysis is incompatible with the use of the boundary-layer approximation. The reader is therefore referred to his paper for the analysis.

Klebanoff & Tidstrom (1959) found $\alpha = 6\,\text{in.}^{-1}$ and $s_1 = 0{\cdot}08$ at $x = 42\,\text{in.}$ Inserting these values in the definition of s_1, we obtain $W_{10}/U_1 = 6\times 10^{-4}$ (0·06 % or 0·04 deg.). On the assumption that the analysis is also applicable to a turbulent boundary layer, which implies the assumptions that the velocity at any

† The author is grateful to Mr R. Woods for pointing this out.

distance above the surface is in the direction of the free stream and that restoring stresses in the (x, z)-plane are negligible, the corresponding figure for the boundary-layer tunnel taking $\alpha = 4\,\text{in.}^{-1}$ and $s_1 = 0{\cdot}1$ at $x = 65\,\text{in.}$, is $W_{10}/U_1 = 8 \times 10^{-4}$. Such small variations in free-stream direction would be very difficult to detect, even in the settling chamber where they are larger by a factor equal to the square root of the contraction ratio.

Physically, we expect spanwise variations in boundary-layer thickness and surface shear stress to become appreciable when the angle at which the free stream is diverging or converging laterally is not negligible compared with the angle at which the boundary layer is growing in the streamwise direction. As this angle is rather less than 0·02 radians, we expect divergence or convergence at 0·002 radians to produce thickness variations of the order of $\pm 10\,\%$. This adds plausibility to the rather startling results of the theoretical calculations. Clearly, quite minor perturbations of the flow through the screens could entirely explain the observed behaviour of the boundary layer.

4. Instability of flow through screens

Morgan (1960) has reviewed the stability of flow through screens of low open-area ratio. Fluid emerges from the plane of the screen as a pattern of jets which tend to stick together in random groups because they can only entrain fluid from each other. The flow is nominally steady. A simple example is shown in figure 3 (plate 1), which is a smoke picture of the flow through a row of parallel cylinders, and in which it can be seen that about 9 jets rapidly coalesce into about 3 groups. Probably the coalescence is less rapid behind a square-mesh grid at lower Reynolds numbers. If the open-area ratio is sufficiently large, the flow will be stable. Morgan refers to the work of Bohl using a grid of sharp-edged slats, who found that open-area ratios β of 0·63 and 0·54 corresponded to a stable and an unstable condition respectively (β is defined as hole area/*total* area of screen). It is evident that the small perturbation required to decide whether a given emerging jet deviates 'left' or 'right' is most likely to be provided by variations in open-area ratio, though if the weave were *very* uniform it might be provided by non-uniformity in the flow approaching the screen. This is not the case in any of the work presented here.

In order to find the critical open-area ratio for square-mesh wire screens in the range of Reynolds number typical of wind-tunnel practice, measurements were made of the surface shear stress on the working-section wall of a small tunnel test rig with various combinations of screens in the settling chamber. (The use of the working-section wall rather than a plate in the middle of the working section is not likely to affect the results greatly. Head used a tunnel wall, while Klebanoff & Tidstrom and Favre & Gaviglio used plates.) The test rig is shown in figure 4. The screens were tacked on to wooden frames of 2 in. thickness, so that the length of the settling chamber varied slightly with the number of screens installed. The honeycomb, two curved 24-mesh 33 s.w.g. screens and a flat 20-mesh 28 s.w.g. screen were retained throughout the tests. A trip wire was fitted at the front of the working section and 6 Preston tubes were mounted at 1 in. transverse intervals about 45 in. downstream of the trip wire on the 9 in.

side of the working section. It should be noted that the Preston tubes were not mounted sufficiently carefully for the recorded pressures to be exactly equal when the surface shear stress was uniform, nor were the surface finish and the quality of the joints sufficiently good for the surface shear stress to be uniform even if the screens were perfect. Moreover, there is no guarantee that the Preston tubes were necessarily at the extrema of the shear pattern. Fixed Preston tubes were preferred to a traversing arrangement merely in order to obtain results as quickly as possible.

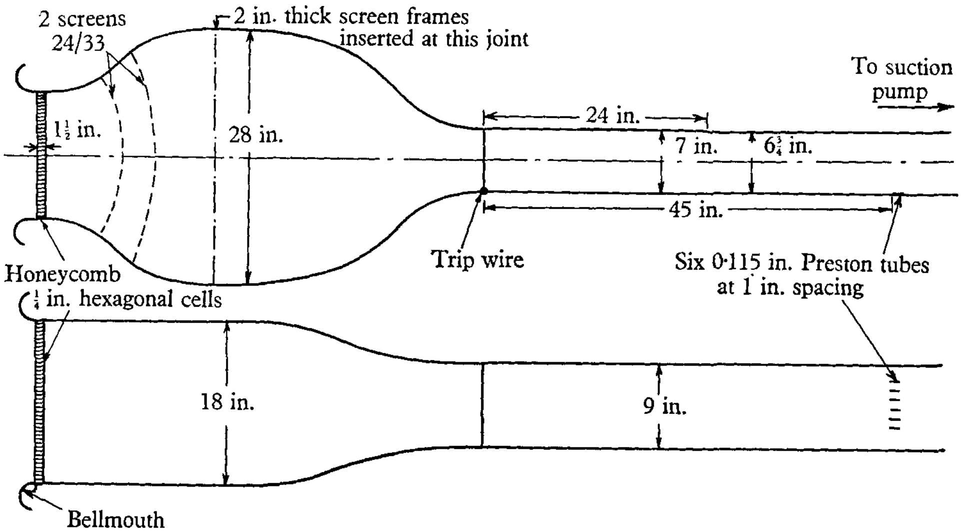

FIGURE 4. Screen test rig.

Measurements were first made of the 'basic pattern' of Preston-tube readings caused by the fixed screens (figure 5 (i)). Then an extra screen was added downstream and Preston-tube readings taken with the last screen in its 'normal' position and with the screen reversed (for convenience the screen frame was rotated through 180° in its own plane and *not* about the y-axis as in the boundary-layer tunnel experiments described above). The difference between the 'normal' and 'reversed' readings was a measure of the disturbance introduced by the least screen. It could also be seen whether the 'basic pattern' was totally altered, or merely reduced in amplitude, by adding a particular screen.

Figure 5 shows the two sets of readings for several different last screens (groups such as 20/28 indicate 20 mesh-per-inch, 28 s.w.g. wire, and so on). It is seen that a screen with $\beta = 0{\cdot}53$ totally changes the pre-existing pattern, and that the pattern is altered when the screen is reversed. On the other hand, a screen with $\beta = 0{\cdot}63$ has little effect on the pre-existing pattern and there is only a small change when the screen is reversed; such a screen is of too high an open-area ratio to suffer from instability, but it is also too open to reduce pre-existing variations in flow direction appreciably. A screen with $\beta = 0{\cdot}57$ achieves the desired result of reducing the pre-existing variations without introducing appreciable variations of its own. Further tests, not shown in figure 5, showed that a screen with

$\beta = 0{\cdot}538$ was 'unstable' and a screen with $\beta = 0{\cdot}565$ was stable on one trial and unstable on another, so that $\beta = 0{\cdot}57$ is confirmed as the stability limit.

We may therefore deduce that the shear-stress variations are, as hypothesized, produced by the screen instability described by Morgan, and that the stability

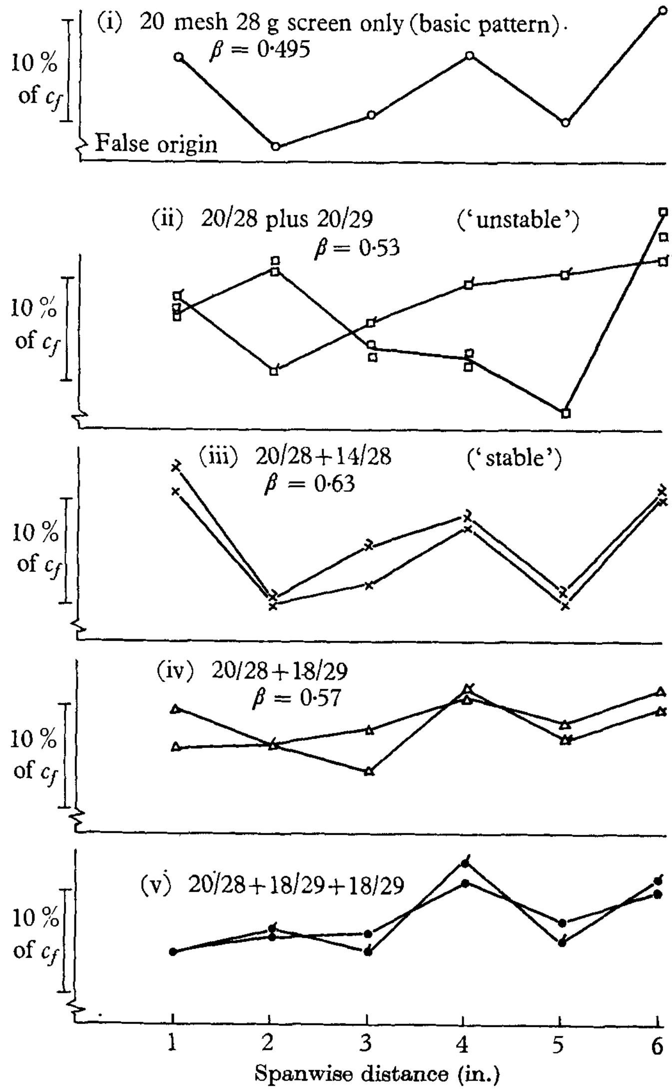

FIGURE 5. Preston-tube readings behind different combinations of screens (screens listed from upstream to downstream). Unflagged symbols—standard position. Flagged symbols—last screen reversed.

limit for this particular range of $Ud/\beta\nu$ (approximately 150) lies between open-area ratios of 0·53 and 0·57, so that open-area ratios of 0·57 and above are probably 'safe' in most circumstances. These figures are compatible with Bohl's results as discussed by Morgan (1960). One wishes to use screens of as *low* an open-area ratio as possible, to achieve a reasonably large pressure-drop coefficient and large reductions of turbulence. Wieghardt (1953) gives the empirical formula

$$K = 6{\cdot}5\frac{1-\beta}{\beta^2}\left(\frac{Ud}{\beta\nu}\right)^{-\frac{1}{3}}$$

for $60 < Ud/\beta\nu < 600$. At the speed of 11 ft./sec at which the measurements of figure 5 were made, this formula gives $K = 1{\cdot}66$ for an 18 mesh, 0·0136 in. screen ($\beta = 0{\cdot}57$). The value measured on the test rig was 1·62.

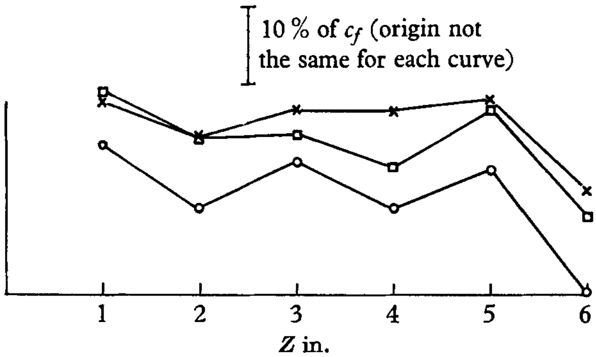

FIGURE 6. Pattern behind 16/28 + 18/29 + 18/29 screen combination, at different speeds in the settling chamber. ○, 5·7 ft./sec; □, 13·5 ft./sec; ×, 15·4 ft./sec.

Figure 6 shows some surface-shear-stress measurements for an 18/29 final screen at several different speeds. The variations in surface shear stress seems to be somewhat more pronounced at the lower speeds but it is not clear whether this is entirely due to the screens or not. (In the boundary-layer tunnel and in Fernholz's measurements (1962), the surface-shear-stress pattern with high-solidity screens was not very dependent on speed.) At any rate, the 18/29 last screen seems to be free from instability in the range $60 < Ud/\beta\nu < 160$ since the results of figure 5 show that the pattern is recognizably the pre-existing pattern determined by the upstream screens.

The four screens downstream of the honeycomb in the N.P.L. boundary-layer tunnel have now been replaced by 16-mesh 28 s.w.g. gauze ($\beta = 0{\cdot}58$; the honeycomb and upstream screens are the same as in figure 1). The resulting spanwise distribution of surface shear stress at $x = 65$ in. is shown in figure 7. These residual variations are attributable to odd wrinkles, non-uniformity of weave (which can itself produce divergence or convergence of the flow) and any non-uniformities produced by the honeycomb or not completely removed from the stream by the honeycomb. Further efforts to remove these variations does not appear worth while. In a strong adverse pressure gradient ($U_1 \propto x^{-0{\cdot}255}$) the surface shear stress at $x = 83$ in. varies about $\pm 7\,\%$ from the mean, but as the surface shear stress only represents about 10 % of the momentum balance the variations are still small enough to be neglected for most purposes.

It therefore seems that, on the basis of these limited tests, wind-tunnel screens should have open-area ratios of 0·57 or more, implying pressure-drop coefficients of not more than about 1·6 at 12 ft./sec in air. Clearly, this criterion applies only to reasonably uniform weave; if a screen with nominal $\beta \geqslant 0{\cdot}57$ had patches with local $\beta < 0{\cdot}57$, it would suffer from instability in these patches. Since directional variations arising in the return circuit may also affect the boundary layer, boundary-layer tunnels should have precision-made honeycombs, as screens and contractions are not very effective suppressors of V- and W-component disturbances. Patel (1964) has recently shown that a precision honeycomb without screens gives adequately two-dimensional results.

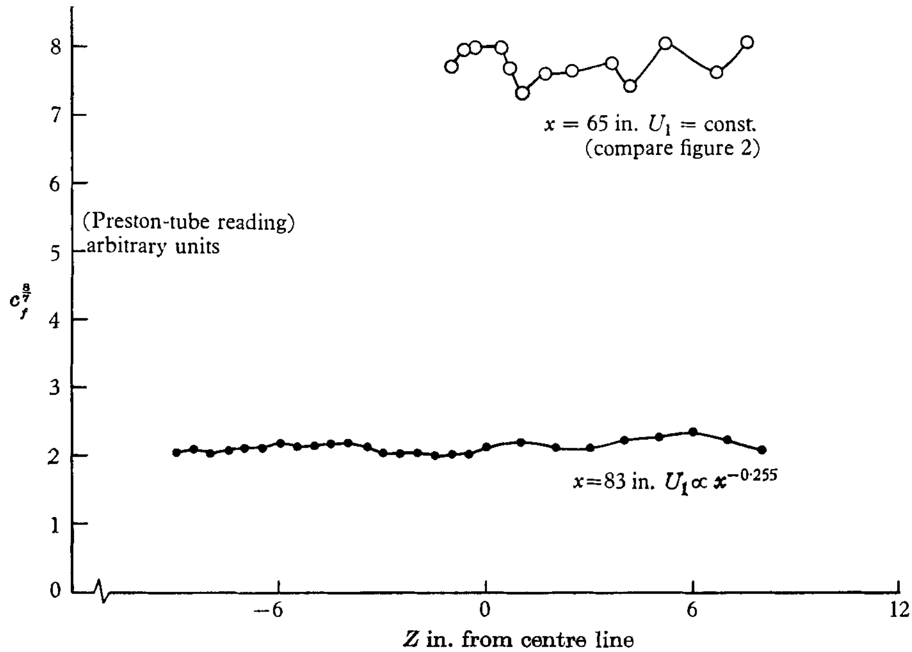

FIGURE 7. $c_f(z)$ in boundary-layer tunnel with 16-mesh 28 s.w.g. screens (β = 0·58).

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