NASA CR-177,023

NASA-CR-177023
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JIAA TR - 66

# A STUDY OF THE FACTORS AFFECTING BOUNDARY LAYER TWO-DIMENSIONALITY IN WIND TUNNELS

BY

R. D. Mehta and P. H. Hoffmann

(NASA-CR-177023) A STUDY OF THE FACTORS AFFECTING BOUNDARY LAYER TWO-DIMENSIONALITY IN WIND TUNNELS (Stanford Univ.) 29 p CSCL 01A
N86-28914
Unclas
G3/02 43287

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MAY 1986

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# A STUDY OF THE FACTORS AFFECTING BOUNDARY LAYER TWO-DIMENSIONALITY IN WIND TUNNELS

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## ACKNOWLEDGEMENTS

The work presented here was supported by NASA Grant NCC 2-294.

## NOMENCLATURE

| | |
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| $C_f$: | Skin friction coefficient |
| d: | Screen wire diameter |
| K: | Screen pressure drop coefficient |
| P: | Total pressure |
| p: | Static pressure |
| q: | Dynamic pressure |
| U, V, W : | Mean velocity components in Cartesian system |
| $U_e$: | Free-stream velocity in the wind tunnel |
| u,v,w: | Fluctuating velocity in the X,Y,Z directions, respectively |
| X, Y, Z : | Cartesian coordinates for streamwise, normal, and spanwise directions, respectively. |
| $\beta$: | Screen open-area ratio |
| $\delta_{995}$: | Boundary layer thickness |
| $\nu$: | Kinematic viscosity |
| $\rho$: | density |
| $(\ )_{cl}$: | center-line value |

## SUMMARY

An experimental study is described on the effect of screens, honeycombs and centrifugal blowers on the two-dimensionality of a boundary layer on the test section floors of low-speed blower tunnels. Surveys of the spanwise variation in surface shear stress in three blower tunnels revealed that the main component responsible for altering the spanwise properties of the test section boundary layer was the last screen, thus confirming previous findings (e.g. Bradshaw, 1965). It was further confirmed that a screen with varying open-area ratio (due to dirt accretion, for example), produced an unstable flow. However, contrary to popular belief, it was also found that for given incoming conditions and a screen free of imperfections, its open-area ratio ALONE was not enough to describe its performance. The effect of other geometric parameters such as the type of screen, honeycomb and blower were investigated. In addition, the effect of the order of components in the settling chamber, and of wire Reynolds number were also studied. Section 1 of this report includes a detailed review of previous work on the subject.


## 1. INTRODUCTION

One of the main goals when designing a wind tunnel is to produce a uniform mean flow with a low turbulence intensity level in the test-section. This is usually achieved by installing a honeycomb and three to four screens in the settling chamber, a contraction with an area ratio of about ten and ensuring that boundary layer separation does not occur in any of the wind tunnel legs (see Mehta, 1977 and Mehta and Bradshaw, 1979 for details on wind tunnel design). Aspect ratios (width to height) of five to six are typically used for test-sections in which a two-dimensional flow (a two-dimensional boundary layer on the test section floor or test plate) is desired. However, it is now widely known that a uniform core-flow and a large aspect ratio does not necessarily guarantee a two-dimensional boundary layer in the test-section. Large spanwise variations (10-20% or more) in boundary layer thickness, surface shear stress and turbulence intensity are often encountered in what is thought to be a two-dimensional boundary layer (Morkovin, 1979). More often than not, it is this lack of two-dimensionality which leads to discrepancies between theory and experiment. This is especially true when two-dimensional calculations or data analyses are used to predict experiments which are assumed, but not verified, to be two-dimensional.

Klebanoff and Tidstorm (1959), Benney (1961), Head and Rechenberg (1962) and Fernholz (1962) investigated this quasi-periodic spanwise variation and attributed it to the generation of secondary vortices originating in the course of natural transition in boundary layers from a laminar to a turbulent state. In the absence of a boundary layer trip, a variation in transverse transition position is obtained due to small local disturbances. However, transverse variations in the boundary layer properties were found to exist even in uniformly tripped boundary layers. Several researchers have studied and described this effect. It has been described in terms of an instability that occurs downstream of low open-area ratio (high solidity) screens.

Corrsin (1944, 1963) showed how the level of homogeneity behind a periodic grid was affected by the grid solidity. He proposed that if the individual wakes (or jets) merge without shifting their axes laterally, than an accurately constructed grid will generate a reasonably homogeneous field at large streamwise distances. However, if the wake system is unstable, as in a grid of high solidity, the individual jets will "coalesce successively into larger and larger jets by actual direction changes." He also proposed that the value of grid solidity above which the instability will occur will depend on the shape of the grid elements, hence suggesting that the fluid dynamic solidity should be considered rather than the geometric one. The present findings are in agreement with this suggestion.

For screens with $\beta < 0.5$, Baines and Peterson (1951) observed the instability by noting appreciable and unsteady differences between measured and expected downstream profiles. This was attributed to local minute variations in wire diameter and spacing so that the jet flow through each element of the screen would either coalesce with or diverge from its neighbor in a fairly random manner.

Morgan (1960) reviewed the stability of flow through screens of low open-area ratio. He found that in certain cases, the flow behind a uniform screen was unstable with both spatial and temporal variation. He suggested that the physical mechanism of this instability depended "upon the entrainment of air by individual jets from the wakes between them." The flow pattern behind the screen would then consist of jets which coalesce in random groups. Morgan also suggested that, for given fluid dynamic conditions, the appearance of the instability would depend on the screen open-area ratio. Screens of low $\beta$, where the distance between neighboring jets is relatively large, were found to be more susceptible to the instability. Morgan refers to the work of Bohl using a grid of sharp-edged slats, who found that open-area ratios of 0.63 and 0.54 corresponded to a stable and an unstable condition, respectively. Morgan warned that the instability may also be influenced by irregularity in the spacing of the screen wires and raised the question whether dirt accretion on the screen wires would also affect the stability - it is shown below in the present results why Morgan's concern was thoroughly justified.

By measuring spanwise variation of surface shear stress, Bradshaw (1964 and 1965) tested various combinations of screens in order to find the optimum open-area ratio. His results indicated that a screen which is nominally free of imperfections and $\beta = 0.57$ "achieves the desired result of reducing the pre-existing surface shear stress variations without introducing appreciable variations of its own." A screen with $\beta = 0.63$ had little effect on the pre-existing pattern whereas the one with $\beta = 0.53$ totally changed the pattern for the worse. The variations in surface shear stress were almost independent of Reynolds number in the usual range encountered in low-speed wind tunnels. Bradshaw also attributed the mechanism to spatial instability of the multiple jets emerging from the pores of the screen. The random coalition of jets emerging from a monoplane grid is nicely illustrated in Fig. 3 of Bradshaw (1965). Bradshaw also showed theoretically how boundary layers are very sensitive to small variations in free-stream direction. He therefore recommended that wind tunnel screens should have reasonably uniform weave and open-area ratios of 0.57 or more. A screen with $\beta = 0.57$ gives a pressure drop coefficient of about 1.6 at $Re \sim 100$. Since an overall K of 2.8 is required to produce a uniform downstream profile, regardless of the upstream profile (Taylor and Batchelor, 1949), Bradshaw recommended using multiple screens.

By systematically testing various combinations of screens, honeycombs and transition devices. de Bray (1967) confirmed the findings of Bradshaw (1965) that the transverse irregularities originate behind wind tunnel screens, the degree of non-uniformity being simply a function of the screen open-area ratio.

The spanwise irregularities were always found to persist for appreciable distances downstream of the screen and had a roughly sinusoidal variation with a wavelength of about $2\delta_{995}$. The popular model that evolved therefore consisted of the spatial instability leading to the formation of weak longitudinal vortices in the boundary layer with the vortex diameter approximately equal to the boundary layer thickness. Perkins (1970), based on arguments using the production term in the streamwise vorticity equation, also suggested that the "peak-valley" spanwise variation of surface shear stress was consistent with the presence of longitudinal vorticity in the boundary layer. Longitudinal vortices, once formed, persist for long distances downstream, even in a turbulent boundary layer, since the decay of the vortices under the action of Reynolds stresses is slow because their circulation is reduced only by the spanwise component of skin friction (Mehta et al., 1983). The vortices are also very effective at producing spanwise variation of boundary layer thickness and surface shear stress in a nominally two-dimensional boundary layer (see Shabaka et al., 1985).

The most detailed experimental study to date on spanwise nonuniformity in nominally two-dimensional boundary layers is that due to Furuya et al. (1979) - see also Furuya and Osaka, 1975; Furuya et al., 1975 and Furuya et al., 1976. They conducted flow visualization studies using hydrogen bubbles and measured spanwise profiles of surface shear stress, mean velocity and turbulence intensity. The flow visualization results confirmed the previous findings that screens with $\beta < 0.57$ produce an unstable flow with noticeable spanwise variations in velocity. The measurements downstream of a screen with $\beta = 0.41$ showed similar spanwise variations ($\sim$ 10% peak to peak) in surface shear stress and mean velocity profiles in the boundary layer. Further downstream, the variations in spanwise distribution remained fixed but the magnitude increased to about 15%. The turbulence intensity profiles also showed spanwise variations, but negatively correlated with the velocity distributions. All these observations are consistent with the belief that the boundary layer contains weak but steady and organised longitudinal vorticity. Furuya et al. (1979) in fact went further, and by measuring mean spanwise velocities in the boundary layer, confirmed the presence of counter-rotating pairs of longitudinal vortices with a core size approximately equal to $\delta_{995}$. Measurements in the natural transition case (without a trip) showed large spanwise periodic variations with a large wavelength in the transition region. However, far downstream, once the boundary layer had become fully turbulent, these variations disappeared but the variations with small periodicity remained fixed and were similar to those obtained in the tripped case. This implies that the irregularities due to natural transition probably do not emalgamate into longitudinal vorticity since the vorticity would not be expected to diffuse easily.

Furuya et al. (1979) found that the spanwise non-uniformity had a strong effect on the boundary layer momentum thickness with variations (peak to peak about the mean) of 25% to 35%. They also showed that for the observed spanwise variations, the two-dimensional momentum integral equation cannot be applied, even to individual longitudinal slices, since spanwise transfer of momentum and turbulence would be significant. However, the flow is not so distorted as to make erroneous the validity and use of the conventional log-law in determining skin friction. Furuya et al. also attempted to obliterate the spanwise variations by adding surface roughness or artificial vortices at the section leading edge but both these attempts met with very limited success.

Wood (1980) found that spanwise non-uniformities in a nominally plane mixing layer could be correlated with non-uniformities in the initial boundary layer. However, in contrast to the boundary layer, the non-uniformities in the mixing layer were found to decay with increasing distance downstream. The difference was attributed (Wood, 1982) to the production term in the streamwise vorticity equation (see Perkins, 1970), which contains an anisotropy parameter ($\overline{v^2}$ - $\overline{w^2}$). In a mixing layer, $\overline{v^2}$ is comparable to $\overline{w^2}$, whereas in a boundary layer, the inequality between these two normal stresses is maintained by the inhibiting effect of the wall on $\overline{v^2}$.

It would seem from the review of previous work discussed above that factors affecting the spanwise uniformity in a boundary layer and the mechanisms responsible for it are now almost fully understood. The present investigation stemmed from an unexpected finding that the screen open-area ratio ALONE is NOT enough to define the stability of the emerging flowfield. Two screens of the same open-area ratio ($\beta$ = 0.578), but different mesh size and wire diameter were found to behave VERY differently. This led to a detailed investigation in which screens and combinations of screens and honeycomb were swapped between three blower tunnels of nominally the same design, in order to try and establish the new (unknown) parameters responsible for this behavior. While the results presented in this report are not totally conclusive, they do offer an important warning that spanwise properties of boundary layers in wind tunnels designed for two-dimensional work must be checked regularly, even if all the screens installed in the settling chamber satisfy the criteria based on open-area ratio.

The present report only deals with the effect of screens on boundary layer two-dimensionality in wind tunnels. Screens are specifically installed in wind tunnels to improve mean flow uniformity and to reduce the turbulence intensity levels. Note that the criteria for these primary screen functions are somewhat different to those for boundary layer two-dimensionalty and are not discussed specifically in this report. For a general review on flow through screens see Laws and Livesey (1978). A detailed account of turbulent flow through screens, in particular turbulent boundary layers, is given in Mehta (1978 and 1985).

Details of the experimental set-up and procedure are given in Section 2. Section 3 contains the results and the discussion is given in Section 4. The concluding remarks are presented in Section 5.

## 2. EXPERIMENTAL APPARATUS AND TECHNIQUES

The main experiments were performed in three 0.76 X 0.13 m (30 X 5 inch) blower tunnels located in the Aeronautics Department at Imperial College, London. All three tunnels had the same basic design and dimensions, corresponding to the schematic shown in Fig. 1. Detailed description of this particular wind tunnel design is given by Bradshaw (1972). All three tunnels were driven by centrifugal blowers with backward facing blades.

Tunnels A and B had impellers with aerofoil-type blades whereas tunnel C had 'S'-type blades. The differences in performance of these blowers are discussed in Mehta (1977). The settling chamber of each tunnel comprised of a 5 cm long honeycomb (mesh size ~ 6.5 mm), one screen upstream of the honeycomb and at least two downstream of it. Details of the screens investigated in the present study are tabulated in Fig. 3. Wind tunnels A and B had all Brass screens whereas wind tunnel C had all Plastic Coarse screens. The honeycomb in wind tunnel C had a finer mesh ~ 3 mm. Measurements of the spanwise surface shear stress were made at the end of a 1.5 m long test section by sliding a 2 mm diameter Preston tube across the floor. The Preston tube and a local static pressure tapping were connected to a differential Furness pressure transducer. The output from the Furness was monitored on a digital voltmeter with an averaging time constant of 5 seconds. In each tunnel, the boundary layer was tripped at the contraction exit using a 1 mm round wire; this produced a turbulent boundary layer in equilibrium with a thickness ($\delta_{995}$) of about 25 mm at the test section exit at the normal operating flowspeed of 30 m/s. As discussed above, the instability is believed to be in the form of longitudinal vortices with a core diameter approximately equal to the boundary layer thickness. The spacing between the spanwise measurement points was therefore chosen to equal 0.5 $\delta_{995}$ so that most of the peaks and valleys in the surface shear stress variation would be captured. Some measurements were also made in the Department's 1.4 X 1.2m (4.5 X 4.0 ft) low-speed wind tunnel described by Bearman et al. (1976).

## 3. RESULTS

The results are presented in the form of a normalized surface shear stress plotted against spanwise distance. The normalized surface shear stress is defined in the following way:

Normalized Surface Shear Stress =

$$\frac{(P_p - p_{ref})/q_{ref} - ((P_p - p_{ref})/q_{ref})_{cl}}{q_{dat}} X 10^4 \qquad (1)$$

where $P_p$ is the Preston tube reading, $p_{ref}$ is the local static pressure, $q_{ref}$ is the reference dynamic head for the particular run and $q_{dat}$ is a datum dynamic head (average of all the runs). The origin in some of the plots has been shifted and the measured data points are joined by straight lines for easier comparison. In order to compare the variation of the above defined normalized shear stress with the actual skin friction coefficient $(C - f)$, a reprensetative set of data is plotted using both variables in Fig. 2. The skin friction coefficient was evaluated using Patel's (1965) calibration. As seen in the figure, the variation in normalized shear stress units is equivalent to a percentage variation in the skin friction coefficient about the mean.

### 3.1 Effects of the last screen.

All previous work reviewed in Section 1 showed clearly that the last screen in the settling chamber will have a significant effect on the boundary layer two-dimensionality in the test section. This was also confirmed by the present results. In Fig. 3, the effect of changing the last screen from Plastic Coarse to Brass and then to Plastic Fine in wind tunnel A is illustrated. For each change, the amplitude of the pattern is completely different, although the wavelength is about the same (~ 5 cm). The peak-to-peak variation in surface shear stress is reduced from about 20% (Plastic Coarse screen) to 14% (Brass screen) to about 8% (Plastic Fine screen). In wind tunnel B, the basic patterns have a much larger wavelength (~ 12.5 cm) compared to wind tunnel A, for both, the Plastic Coarse and Brass screens in the most downstream location in the settling chamber (Fig. 4). The absolute peak to peak variation is about the same (~ 11%) although, in general, the overall variation over the central half of the test section seems slightly better for the Brass screen. In wind tunnel C, the wavelength of the variations is also relatively large (~ 12.5 cm) but about the same as wind tunnel B (Fig. 5). The peak to peak variation is about 20% for the Plastic Coarse screen but this is reduced to less than half by the Plastic Fine screen. The wavelength is also reduced by about a factor of two.

The effect of rotating the Plastic Coarse screen about the y-axis (back to front) is shown in Fig. 6. The pattern is basically unchanged in both shape and magnitude. Fig. 7 shows the surface shear stress variation measured downstream of the Plastic Fine screen in wind tunnel B on the floor and the ceiling. While the patterns are not exactly the same, the peak to peak variation and wavelength are comparable. Some check measurements of the surface shear stress extrema are also shown to indicate repeatability of the measurements.

### 3.2 Effects of other settling chamber components

The effects of changing conditions in the settling chamber, other than the last screen, were investigated in wind tunnel C. The difference in spanwise surface shear stress distributions between the case when only the last screen was replaced (borrowed from tunnel B) and when the whole settling chamber (including the honeycomb) was replaced is shown in Fig. 8. Both the peak to peak variation and wavelength were reduced somewhat by swapping the whole settling chamber. Since the honeycomb in wind tunnel C had a finer mesh than the one in tunnel B, the effects due to this difference were also investigated. However, as illustrated in Fig. 9 there is no discernible difference due to the honeycomb mesh size. Also, installing two Plastic Coarse screens (instead of the usual one) upstream of the honeycomb had no effect on the spanwise variation of surface shear stress as shown in Fig. 10.

### 3.3 Effects of age on screen performance.

Prolonged wind tunnel running usually results in the deterioration of screen performance through two effects. Screen sagging due to wind loading can affect the open-area ratio if the wires begin to slide over eachother. This in turn can affect the flow stability as discussed in Section 1. Dirt accumulation on the screen wires can also affect the open-area ratio and if patches with $\beta < 0.57$ result, then this will again cause the emerging flow to be unstable. In addition, dirt accumulation may also affect the flow stability directly by influencing the jet and wake direction. Fig. 11 shows the spanwise surface shear stress variation measured in the 1.4 X 1.2 m test section before and after vacuuming the last screen in the settling chamber. The peak to peak variation about the mean was reduced from about 16% to 6%. However, Fig. 12 shows two spanwise profiles measured four months apart during which time the tunnel was run for approximately 300 hours. The excellent repeatability is a tribute to the efficiency of the inlet filters in not allowing dust particles to enter the wind tunnel. It also implies that the Plastic fine screen maintains is original uniform weave over long periods of running.

### 3.4 Effects of Reynolds Number.

The effects of reducing the Reynolds number based on wire diameter ($Re_d$) for the Plastic Coarse screen by a factor of two were investigated in wind tunnel C. The factor of two was used to determine if the Plastic Coarse screen would behave better at the same wire Reynolds number as the Plastic Fine screen; the wire diameter of the Plastic Fine screen being half that of the Plastic Coarse screen. However, as illustrated in Fig. 13, there was no change in the size and location of the extrema for the Plastic Coarse screen at the lower $Re_d$.

## 4. DISCUSSION

While the results presented in this report confirm several of the conclusions from previous investigations, they also raise some new issues.

Contrary to popular belief, the present results clearly show that the open-area ratio alone of the last screen in the settling chamber is not enough to define its performance. This is seen in the contrasting performance of the Plastic Fine and Plastic Coarse screens, both of which have exactly the same geometric open-area ratio ($\beta = 0.578$). At first, it was reluctantly concluded that the Plastic Coarse screen was PRODUCING maximum instability. The reluctance was inspired by the results of a separate investigation (Mehta, 1978) where the effect of a variety of screens (including the screens used in the present investigation) on the flow in a wind tunnel test section was investigated. In that case, since the incoming flow was uniform, instabilities produced by the screen could be studied independently. It was found that the Plastic Coarse screen produced the most uniform core flow i.e. minimum instabilities. Also, the results in Fig. 6 show no significant change in the pattern when the screen was rotated back to front - the pattern would be expected to change (reversed along z-axis) if it was being produced by that screen. So the implication is that the Plastic Coarse screen, while not suppressing instabilities, does not produce any either. The Plastic Fine screen clearly acts as a suppressor whereas the Brass screen is probably a partial suppressor. This trade-off between suppression and generation was in fact also implied by Bradshaw (1965). He found that the screen with $\beta = 0.63$ had little effect on the pre-existing pattern and concluded that "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." He also concluded that a screen with $\beta = 0.57$ achieves the desired result of reducing pre-existing variations without introducing variations of its own.

The real question is what, apart from the screen open-area ratio, affects the stability of the flow emerging out of a screen. One candidate is the screen pressure-drop coefficient since this is related to $\beta$. In fact, Corrsin (1963) also suggested that the fluid dynamic $\beta$ be considered for stability purposes instead of the geometric one. The Plastic Fine screen does have the highest pressure-drop coefficient at a given Reynolds number. The most optimum formulation for K is that due to Wieghardt (1953) (see Mehta, 1978) and is defined as:

$$K = \frac{\Delta p}{\frac{1}{2}\rho U^2} = 6.5\frac{(1-\beta)}{\beta^2}\left[\frac{Ud}{\beta\nu}\right]^{-1/3} \tag{2}$$

Now, for a given screen and $\nu$, K can be varied by changing U. But, as shown in Fig. 13, increasing K for the Plastic Coarse screen to the same value as that for the Plastic Fine screen (by halving U) had no significant effect. Also, at a given Re, K for the Plastic Coarse screen is higher than that for the Brass screen which acts as a partial suppressor. So it seems that K is not an adequate parameter to define screen performance, although Bradshaw (1965) noted a slight deterioration in the performance of a $\beta = 0.57$ screen at lower flow speeds.

In general, when selecting screens for wind tunnel applications, one chooses screens with $\beta > 0.57$ to minimize the PRODUCTION of directional instabilities and a wire diameter so that $Re_d < 50$ to avoid vortex shedding from the wires. However, for SUPPRESSION of pre-existing variations, the present results show that a criterion based on open-area ratio alone is not adequate. The bottom line is that after any new installation or cleaning of screens, the spanwise uniformity of a supposedly two-dimensional boundary layer must be checked. Since the local changes in flow direction are small and hence difficult to measure, the quantity most suited for this check is the spanwise surface shear stress. The spanwise variation of surface shear stress is adequately measured by sliding a Preston tube across the test-section floor. Note that installing a plate on the centre-line of the test section and studying the boundary layers on it does not eradicate this problem of the directional instability. It can, however, reduce problems due to secondary flows formed on contraction walls (Mehta and Bradshaw, 1979, Mokhtari and Bradshaw, 1983). Although, note that a horse-shoe vortex will form in the junction between the plate and the tunnel wall, each leg of which will grow with streamwise distance. Note also, that the plate leading edge shape will affect the size, strength and position of each leg of the horse-shoe vortex (Mehta, 1984).

Changing components in the settling chamber, other than the last screen, has interesting but predictable effects. Honeycombs are normally too open for either suppression or production of instabilities, as confirmed in Fig. 9. However, changing the upstream screens (screens installed between the honeycomb and the last screen) from Plastic Coarse to Brass would be expected to, and does, affect the eventual pattern as shown in Fig. 8.

Two points emerge from the results of prolonged running effects on screen performance. Screens must be cleaned periodically since dirt accumulation will affect the open area ratio, and possibly the flow stability through this criterion, and it could also affect the flow stability directly by influencing the jet/wake directions. Also, since the plastic screens have necked nodal points (Mehta, 1978), they tend to maintain their original uniform weave better than the metal screens. The need for regular cleaning of the screens and checking of the spanwise properties of a two-dimensional boundary layer connot be overemphasized. Since the local changes in flow direction are small and hence difficult to measure, the quantity most suited for this check is the spanwise surface shear stress which is adequately measured by sliding a Preston tube across the test section floor.

## 5. CONCLUDING REMARKS

The main conclusion from this work is that the widely accepted criterion for flow stability through a screen based on geometric open-area ratio ALONE is not enough. It is clearly shown that two screens with exactly the SAME $\beta$ may behave in completely different ways, one being a suppressor of instability while the other acting totally dormant. While the exact parameters responsible for this difference are not obvious, it seems that a screen with $\beta$ more than 0.57 (to avoid production of the instability) and a small wire diameter ($Re_d < 50$, to avoid vortex shedding) should be used in wind tunnels designed for boundary layer work. In any case, the two-dimensionality on the test section floor or test plate MUST be checked regularly by making spanwise measurements of the surface shear stress.


## ACKNOWLEDGEMENTS

We are grateful to our colleagues, Dr. Aki Nakayama and Mr. Paul Inman for help in obtaining some of the data. Helpful comments by Drs. R.V. Westphal and D.H. Wood on a draft of this report are also gratefully acknowledged.

## REFERENCES


1. Baines. W.D. and Peterson. E.G. An investigation of Flow Through Screens. Trans. ASME. Vol. 73, pp. 467. 1951.

2. Bearman, P.W., Harvey. J.K. and Gardner. C.M. Preliminary calibration of the 4.5 X 4.0 ft. low speed wind tunnel. Imperial College Aero Report 76-01, 1976.

3. Benney, D.J. A Non-Linear Theory for Oscillations in a Parallel Flow. J. Fluid Mech., Vol. 10, pp. 209, 1961.

4. Bradshaw, P. Wind Tunnel Screens: Flow Instability and its Effect on Aerofoil Boundary Layers. J. Roy. Aeronaut. Soc., Vol. 68, pp. 198 1964.

5. Bradshaw, P. The effect of wind tunnel screens on nominally two-dimensional boundary layers. J. Fluid Mech. Vol. 22, pp. 679, 1965.

6. Bradshaw, P. Two more wind tunnels driven by aerofoil-type centrifugal blowers. Imperial College Aero Report 72-10, 1972.

7. Corrsin, S. Investigation of the Behavior of Parallel Two-Dimensional Air Jets. NACA Rep. 4424, 1944.

8. Corrsin, S. Turbulence: Experimental Methods. Handbuck der Physik, Berlin:Springer, Vol. 8, pp. 523, 1963.

9. de Bray, B.G. Some investigations into the spanwise non-uniformity of nominally two-dimensional incompressible boundary layers downstream of gauze screens. Aero. Res. Council R&M 3578, 1967.

10. Fernholz. H. Three-dimensional disturbances in a two-dimensional incompressible turbulent boundary layer. Aero. Res. Council R&M 3368, 1962.

11. Furuya. Y., and Osaka, H. The spanwise non-uniformity of nominally two-dimensional turbulent boundary layers. (1st report, Characteristics Spanwise Velocity Distribution) Bulletin of the Japan Society of Mechanical Engineers, Vol. 18, pp. 664, 1975.

12. Furuya, Y., Nakamura, I., Osaka, H. and Honda, H. The spanwise non-uniformity of nominally two-dimensional turbulent boundary layers (2nd

report. Wall Shear Stress and Flowfield). Bulletin of the Japan Society of Mechanical Engineers, Vol. 18, pp. 673, 1975.

13. Furuya, Y., Nakamura, I., Osaka, H. and Shimizu, T. The spanwise non-uniformity of nominally two-dimensional turbulent boundary layers (3rd report, Influence of the Streamwise Vortices Arising from The Protrusion). Bulletin of the Japan Society of Mechanical Engineers, Vol. 19, pp. 922, 1976.

14. Furuya, Y., Nakamura, I., and Osaka, H. Three-dimensional Structure of a Nominally Planar Turbulent Boundary Layer. ASME J. Fluids Eng. Vol. 101, pp. 326, 1979.

15. Head, M.R. and Rechenberg, I. The Preston tube as a means of measuring skin friction. J. Fluid Mech. Vol. 14, pp. 1, 1962.

16. Klebanoff, P.S. and Tidstorm, K.D. Evolution of Amplified Waves leading to Transition in a Boundary Layer with Zero Pressure Gradient. NASA TN D-195, 1959.

17. Laws E.M. and Livesey, J.L. Flow Through Screens. Ann. Rev. Fluid Mech., Vol. 10, 1978.

18. Mehta, R.D. The aerodynamic design of blower tunnels with wide-angle diffusers. Prog. Aerospace Sci., Vol. 18, p. 18, 1976.

19. Mehta, R.D. Aspects of the design and performance of blower-tunnel com ponents. Ph.D. Thesis. Aeronautics Department, Imperial College, London, 1978.

20. Mehta R.D. and Bradshaw, P. Design rules for small low-speed wind tunnels. Aero. J. Vol. 83, No. 827, 1979.

21. Mehta, R.D., Shabaka, I.M.M.A., Shibl, A. and Bradshaw, P. Longitudinal Vortices Imbedded in Turbulent Boundary Layers. AIAA Paper 83-0378, 1983.

22. Mehta, R.D. Turbulent flow through screens. AIAA paper 84-0538, 1984. (See also, Turbulent Boundary Layer Perturbed by a Screen. AIAA J. Vol. 23, No. 9, pp. 1335, Sep. 1985.)

23. Mehta, R.D. Effect of Wing Nose Shape on the Flow in a Wing/Body

Junction. Aero. J. Dec., 1984.

24. Mokhtari S. and Bradshaw, P. Longitudinal Vortices in Wind Tunnel Boundary Layers. Aero. J., Vol. 87, pp. 233, 1983.

25 Morkovin, M.V. Observations on Streamwise Vortices in Laminar and Turbulent Boundary Layers. NASA Contractor Report 159061, April, 1979.

26. Morgan, P.G. The stability of flow through porous screens. J. Roy. Aero. Soc. Vol. 64, pp. 359, 1960.

27. Patel, V.C. Calibration of the Preston Tube and Limitations on its Use in Pressure Gradients. J. Fluid Mech. Vol. 23, pp. 185, 1965.

28. Perkins, H.J. The Formation of Streamwise Vorticity in Turbulent Flow. J. Fluid Mech., Vol. 44, pp. 721, 1970.

29. Shabaka, I.M.M.A., Mehta, R.D. and Bradshaw, P. Longitudinal Vortices Imbedded in Turbulent Boundary Layers. Part I. Single Vortex. J. Fluid Mech. Vol. 155, pp. 37,
1985.

30. Taylor, G.I. and Batchelor, G.K. The Effect of a Gauze on Small Disturbances in a Uniform Stream. Quart. J. Mech. Appl. Math., Vol. 2, pp. 1-29, 1949.

31. Wieghardt, K.E.G. On the Resistance of Screens. Aeronaut. Q., Vol. 4, pp. 186, 1953.

32. Wood, D.H. A Reattaching, Turbulent. Thin Shear Layer. Ph.D. Thesis, Aeronautics, Dept., Imperial College, 1980.

33. Wood, D.H. Spanwise Non-Uniformities in a Nominally Plane Mixing Layer. Dept. of Mechanical Eng., University of Newcastle, Report TN-FM 82/3, 1982.

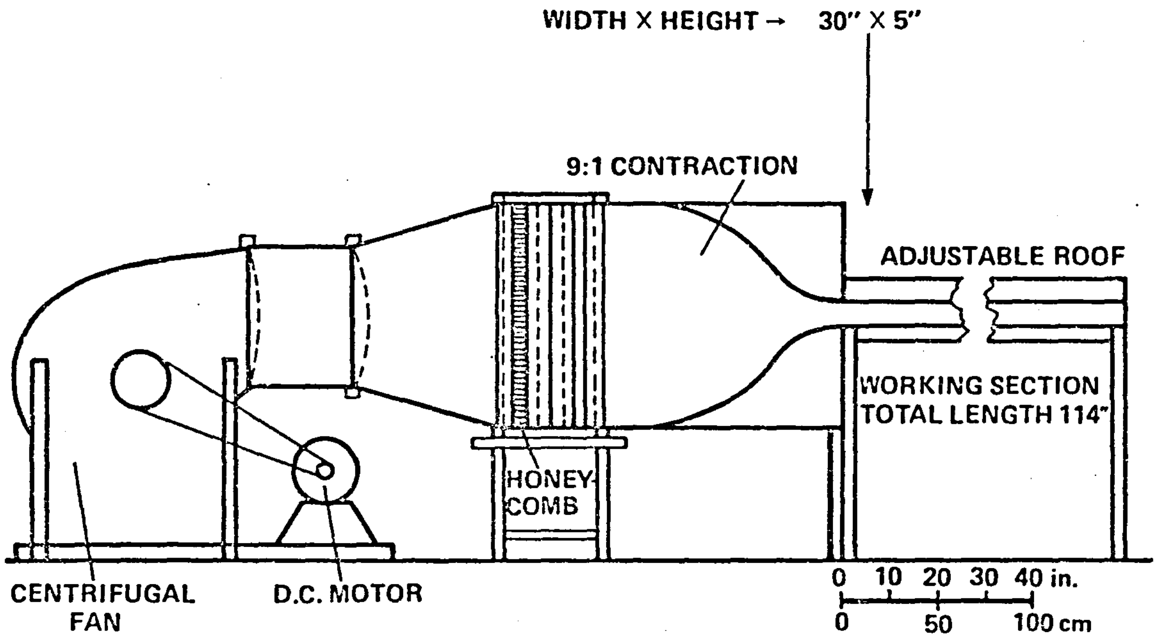


Fig. 1. Schematic of 30 X 5 in Blower Wind Tunnel

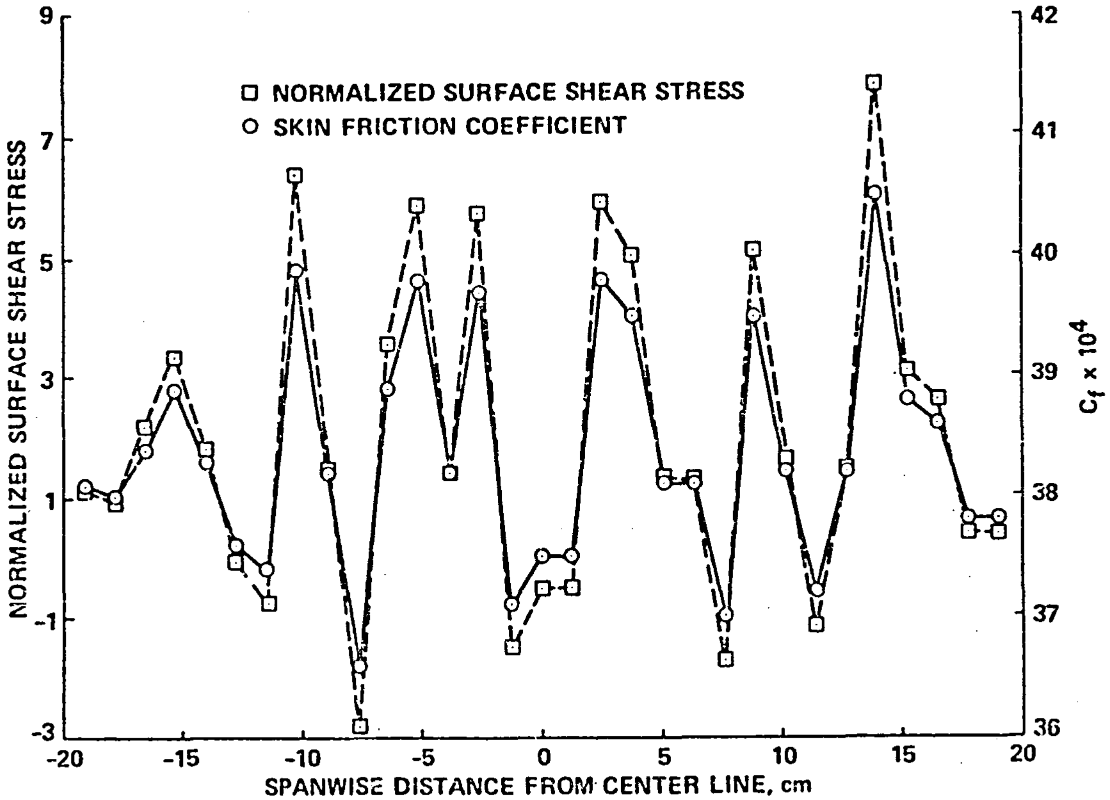


Fig. 2. Comparison of Normalized Shear Stress Definition with Skin Friction Coefficient

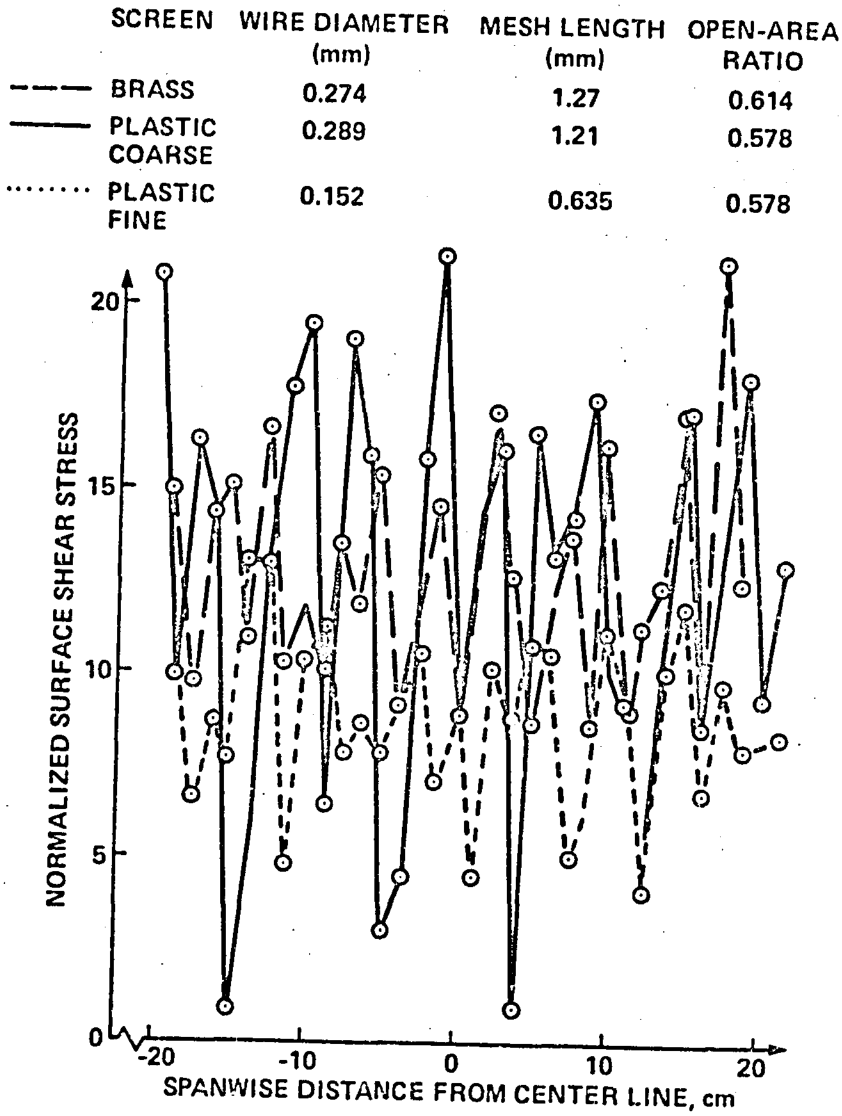


Fig. 3. Effect of Changing the Last Screen in Wind Tunnel A

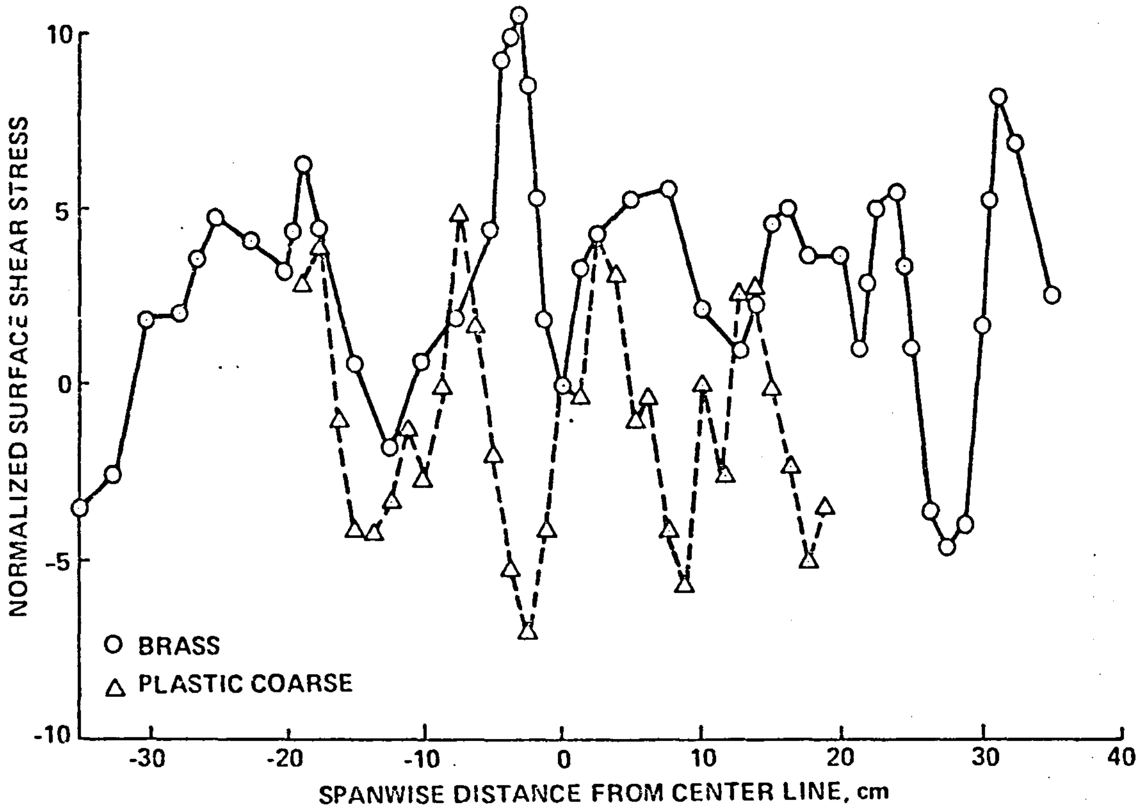


Fig. 4. Effect of Changing the Last Screen in Wind Tunnel B

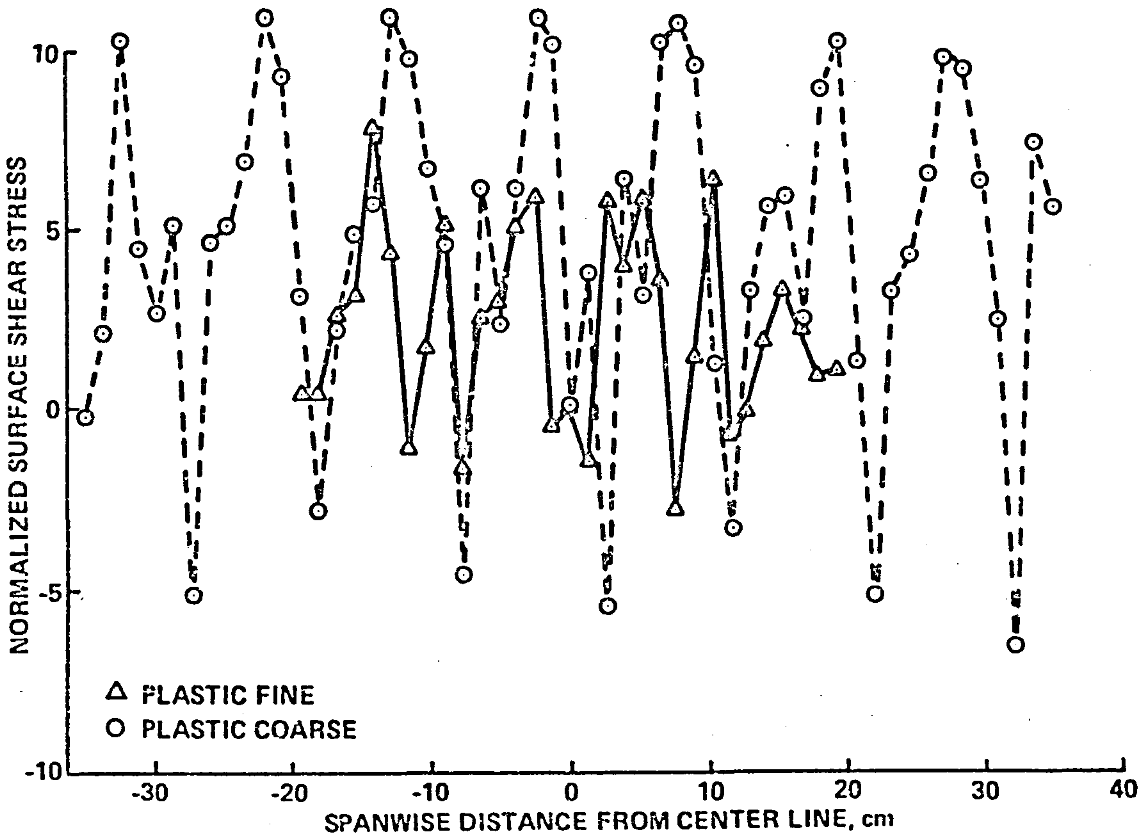


Fig. 5. Effect of Changing the Last Screen in Wind Tunnel C

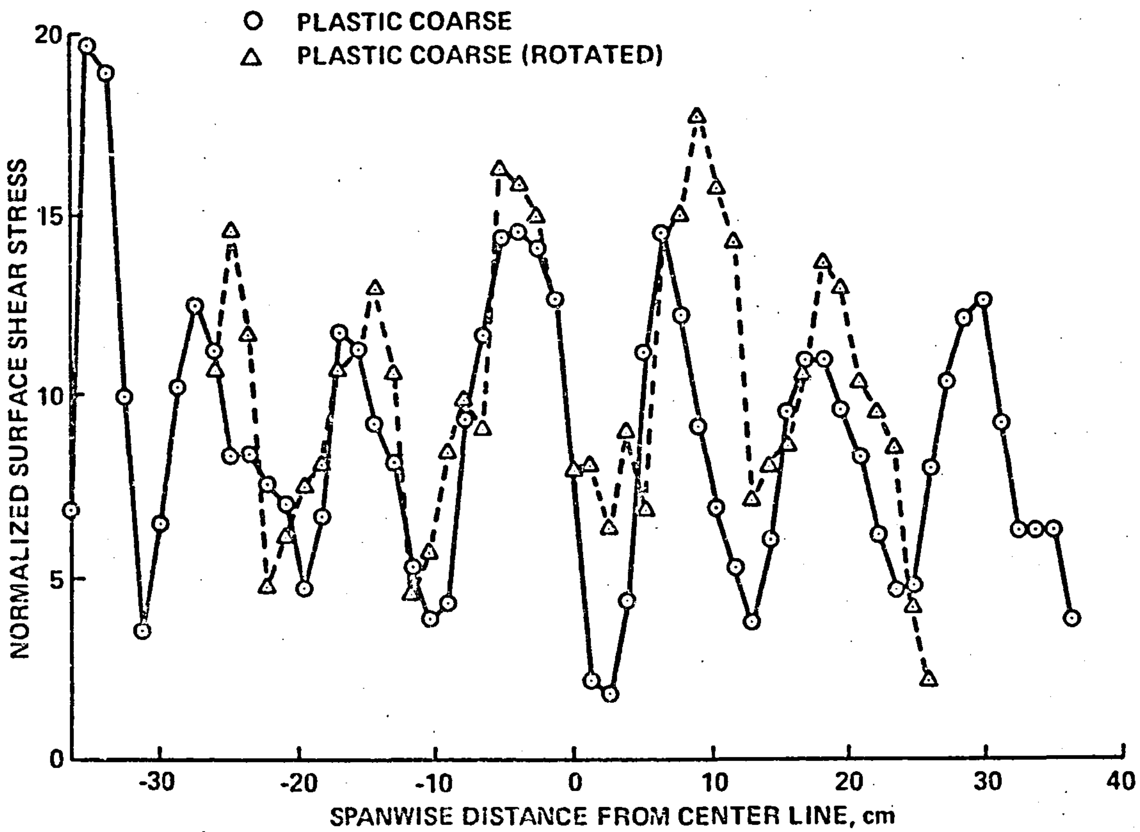


Fig. 6. Effect of Rotating the Last Screen about the Y-axis (back to front)

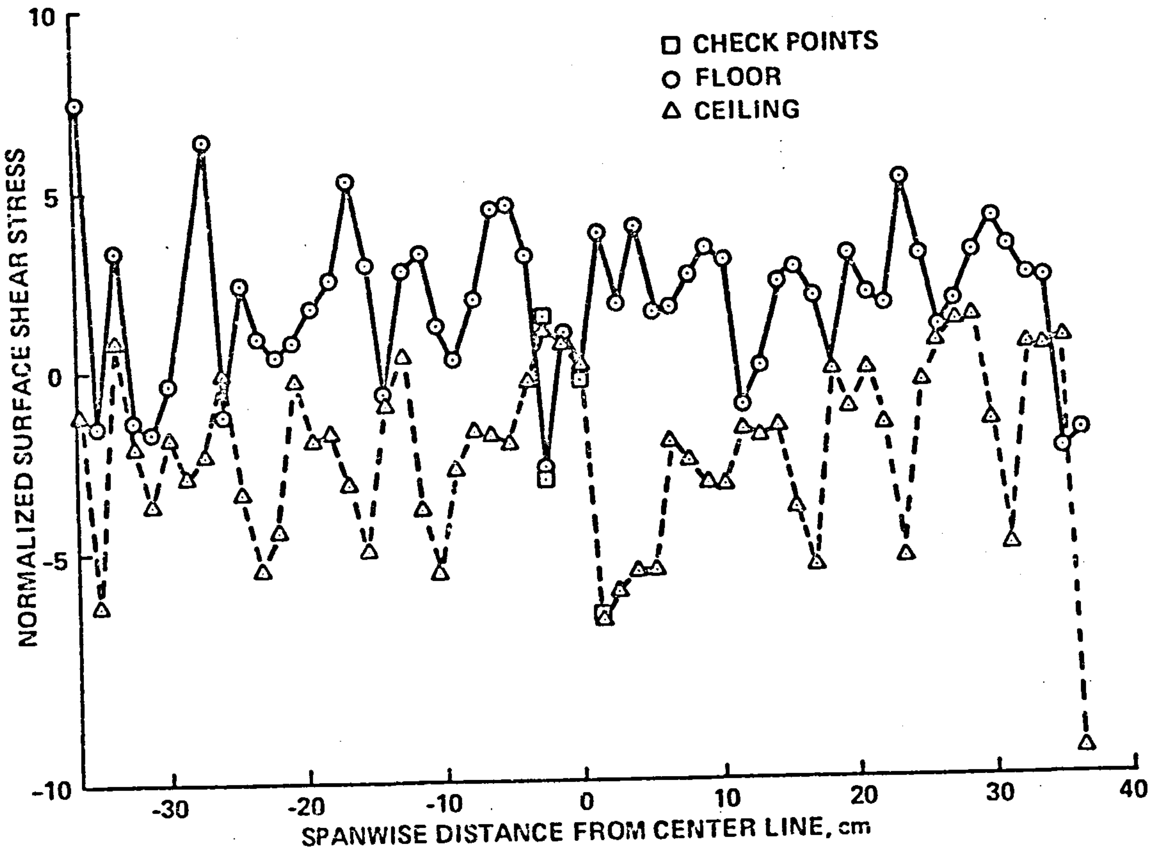


Fig. 7. Comparison of Surface Shear Stress Variation on Test Section Floor and Ceiling downstream of Plastic Fine Screen

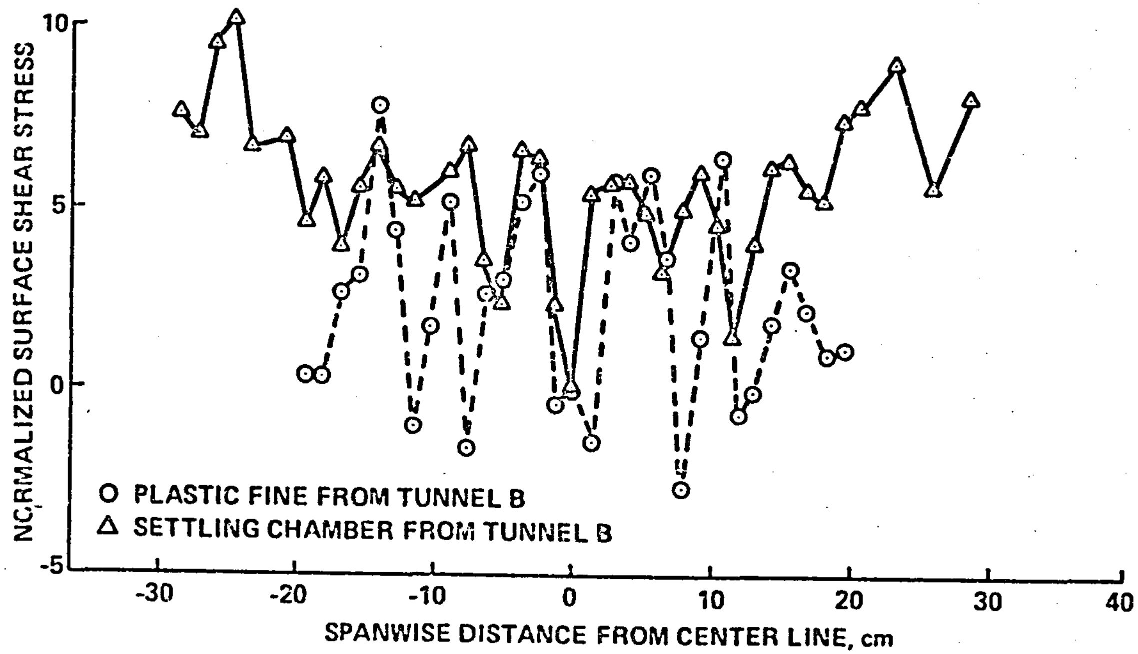


Fig. 8. Effect of Replacing the Last Screen versus Replacing the Whole Settling Chamber in Wind Tunnel C

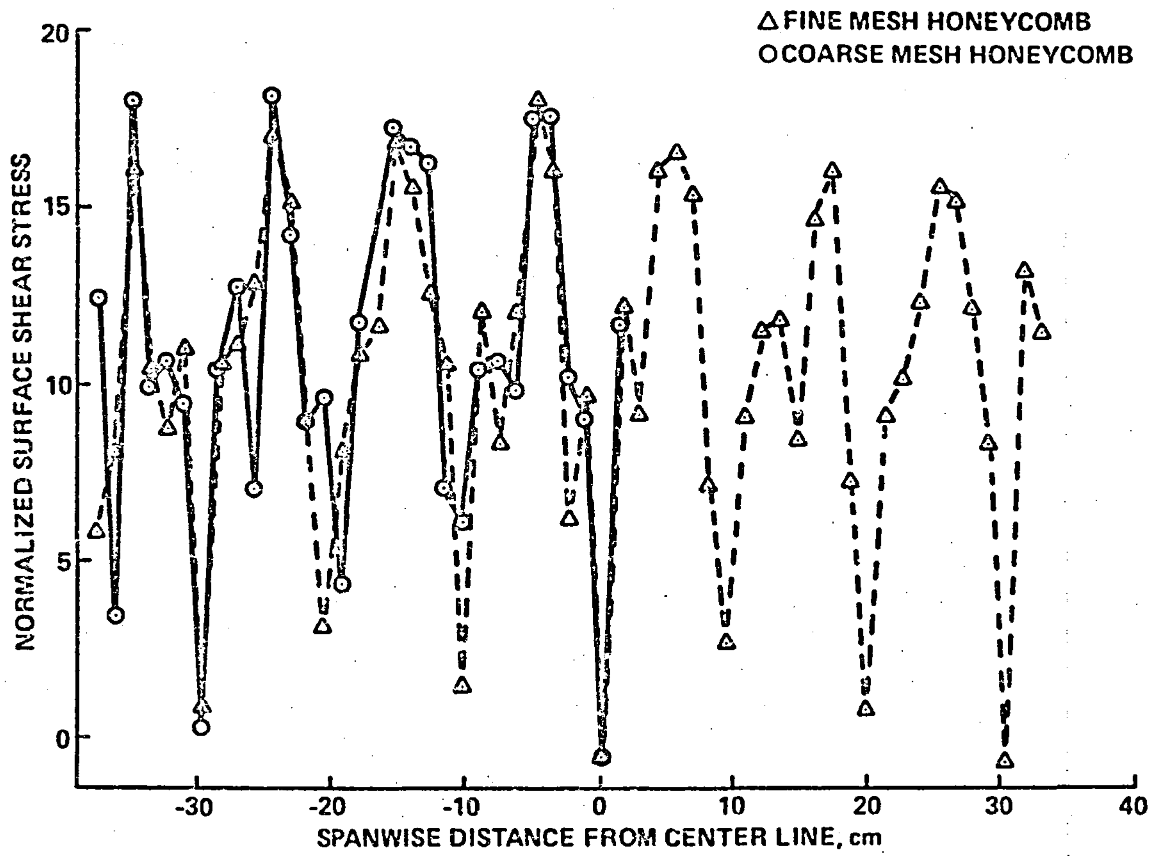


Fig. 9. Effect of Changing the Honeycomb Type

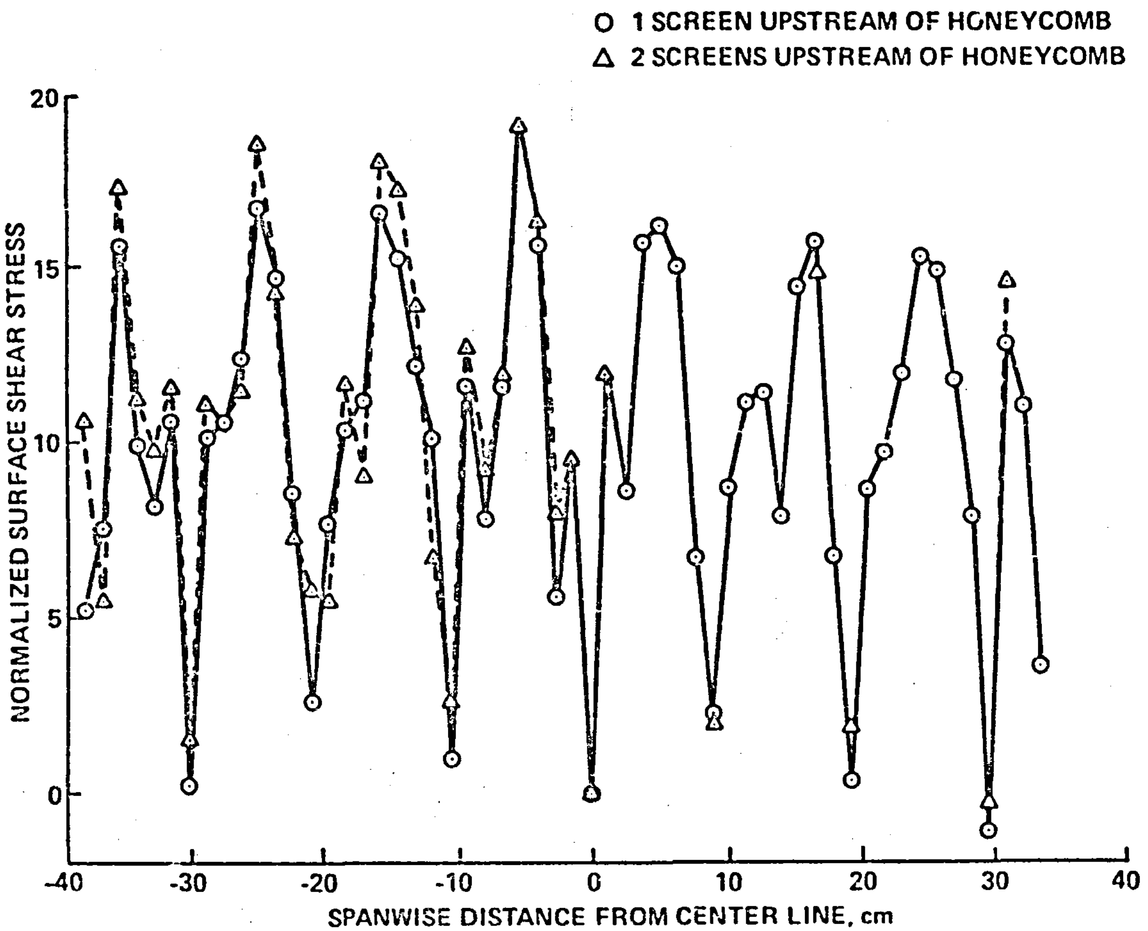


Fig. 10. Effect of Changing the Number of Screens Upstream of the Honeycomb

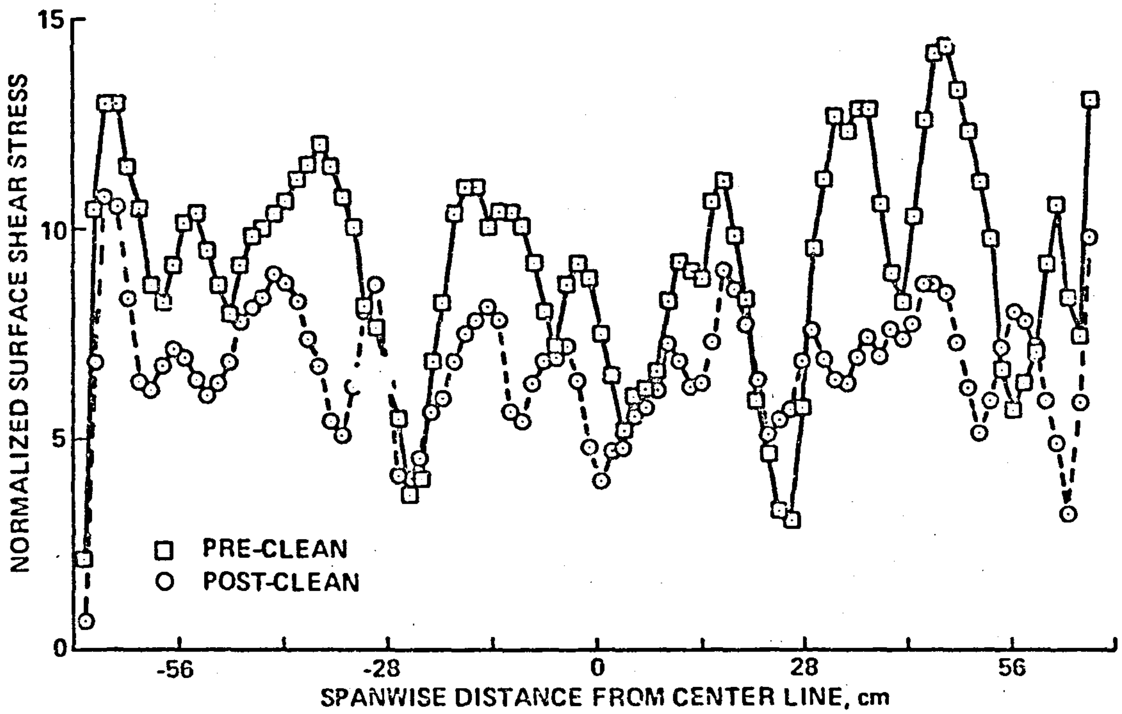


Fig. 11. Effect of Vacuuming the Last Screen in the 1.4 X 1.2 m Wind Tunnel

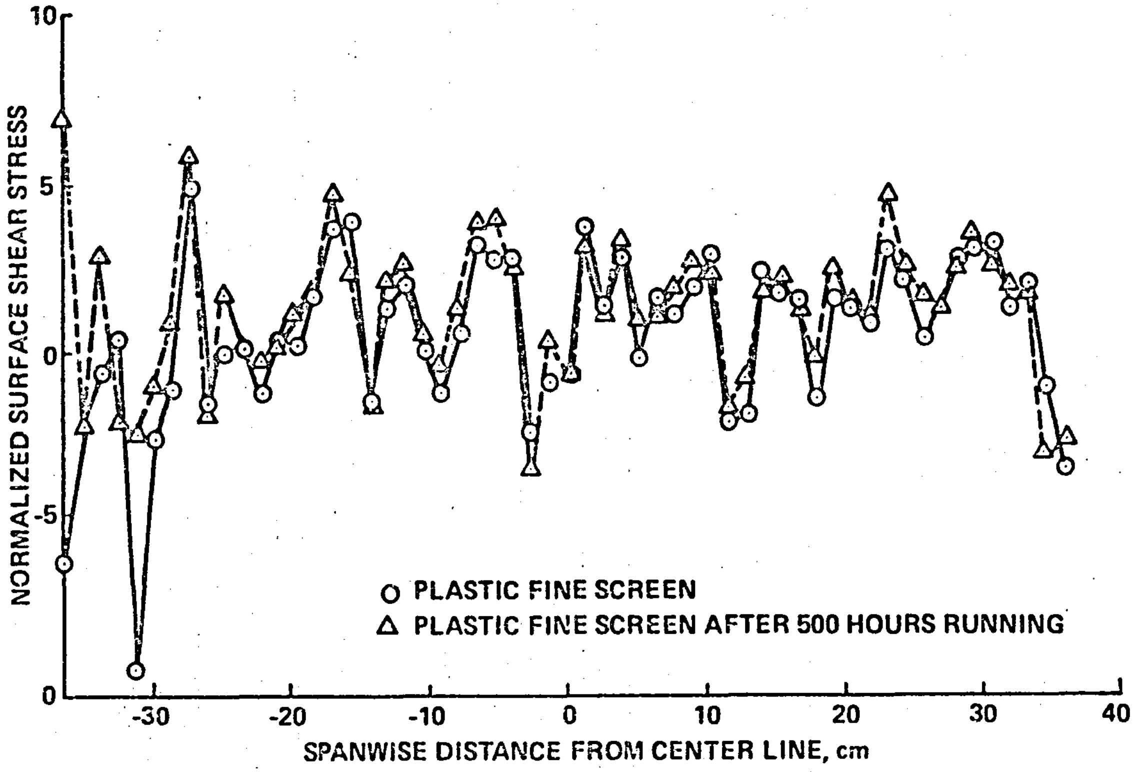


Fig. 12. Effect of Prolonged Running in Wind Tunnel B

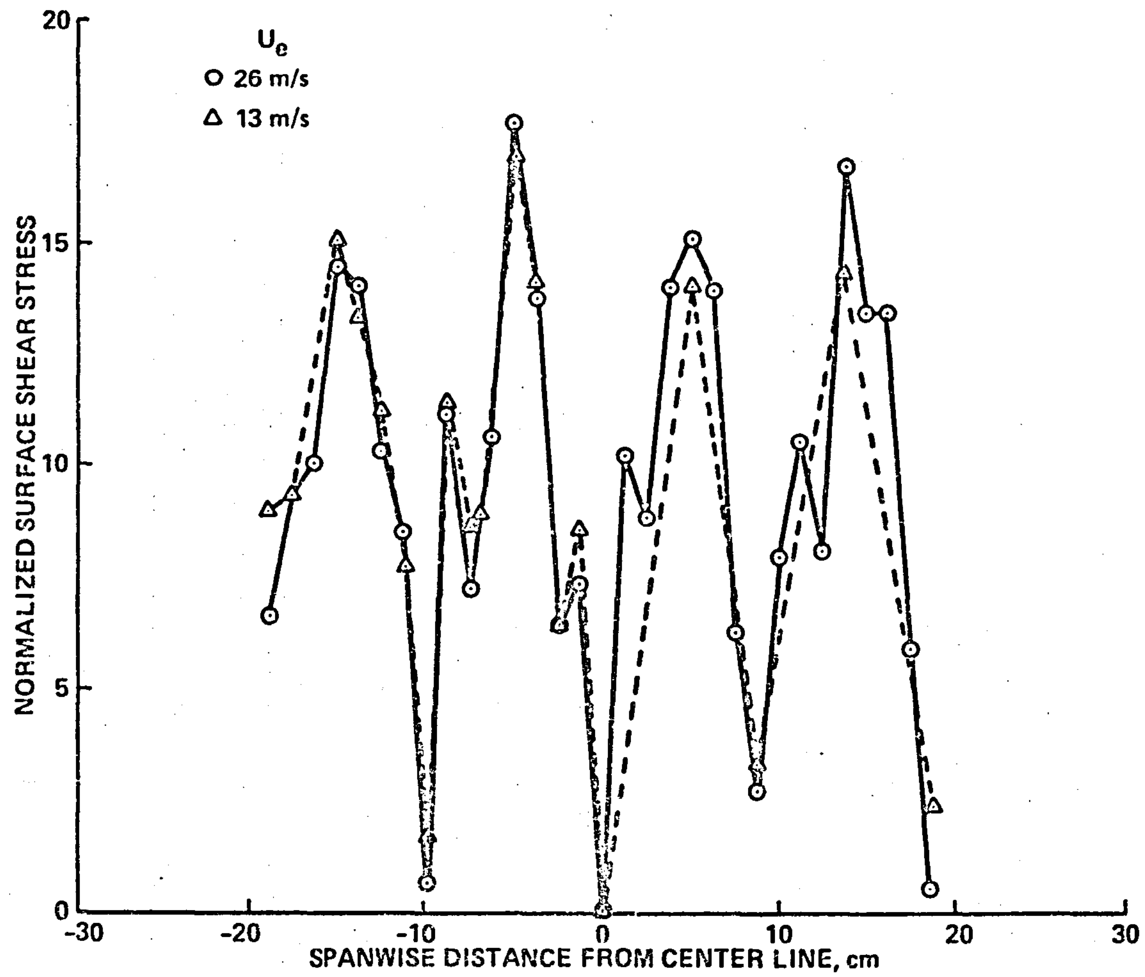


Fig. 13. Effect of Varying Screen Wire Reynolds Number

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