SECTION I, ENGINEERING SCIENCE

Aerodynamic Drag Reduction Using Compliant Coatings[1]

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NOMENCLATURE

C_f, C_F	=	local and average skin friction coefficient, respectively
I	=	turbulence intensity $\equiv \overline{(u_1^2)}^{1/2}/U_1$
T_x, T_z	=	tension in longitudinal (streamwise) and lateral direction, respectively
U_1	=	free stream velocity
u_1, u_2, u_3	=	instantaneous fluctuating components of velocity streamwise, normal to wall and parallel to wall, respectively
x, z	=	position coordinates in the plane of the coating, streamwise and transverse, respectively
ρ	=	density
ν	=	kinematic viscosity

INTRODUCTION

In the last few years, considerable interest has been generated in the area of drag reduction by compliant coatings or flabby skins.

Much of this interest was stimulated by the work of Kramer (1957, 1960, 1961) which indicated a reduction of drag on bodies towed in water by coating the surfaces of the bodies with a compliant coating. The coating was inspired by the flabby skin of the dolphin which, according to Kramer, is responsible for its high speed. The contention is that the dolphin's flabby skin damps the adjacent flow disturbances, thus retarding transition and resulting in a larger area of laminar flow (with low values of skin friction) over the dolphin. Theoretical analyses by Benjamin (1960), Landahl (1962), and Kaplan (1964) indicate that the stability of laminar boundary layer can be altered by the use of compliant boundaries.

The effect of flabby skins in the transition and turbulent region has received a very limited amount of attention. Karplus (1963) investigated the scale and degree of turbulence for water flowing over stretched Mylar film backed with different damping fluids. He found that in his tests, turbulence sets in sooner for the flexible wall than for a solid wall, but grows to its final value more slowly. The damping fluid behind the film made the surface appear more like a solid surface as the viscosity was increased.

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As promising as the initial results of Kramer were, unfortunately only a few experimenters since then have been able to measure a reduction in skin friction drag using compliant coatings. Lauffer and Maestrello (1963), in an experimental study of turbulent air flow in channels lined with thin steel, aluminum, Mylar and fabric membranes, detected no significant skin friction reduction. Smith (1963) using water flow through pipes with annular coatings of elastic gel could not detect any reduction in skin friction. Gregory and Love (1961) investigated the effects of surface flexibility on the drag of a 5-foot-chord airfoil utilizing a foamed sandwich flexible surface and they found no skin friction reduction. Benjamin (1964) reported that Dinkelacker of the University of Southhampton investigated the skin friction of flexible walls and found no decisive skin friction reductions. Stephens (1966) tested corrugated skins of 0.001 in. Melinex (fabricated by Gregory) and obtained no reduction. Ritter and Messum (1964) found a drag reduction of 7%-14% on a Kramer-type coating but the scatter of the data was so large that the results are questionable.

On the promising side were the results of Von Winkel and Barger (1961) and Pelt (1964). Von Winkel and Barger (1961) measured surface pressure fluctuations on a Kramer-type flexible skin and found a considerable reduction in the intensity of the fluctuations. Pelt (1964) found that skin friction in pipe lines could be reduced by as much as 35% by lining the pipe with a flexible tube. The annular space between the flexible tube and pipe wall was filled with a variety of damping fluids (air, water, and solutions of glucose). The flexible tubes used were Texin tubes, Tygon tubes and rubber tubes. Pelt found that Texin tubes gave the biggest skin friction reduction.

INITIAL WIND TUNNEL STUDY

The initial work done at the University of Oklahoma was started in 1963. Since a search of the literature revealed that a very little experimental work had been done with flabby skins in an air flow it was decided to conduct some exploratory work in a wind tunnel. For an exploratory experiment it was decided to measure the turbulent intensity of flow in the turbulent wake of a small fence along a flat plate covered with a flabby skin.

Rather than measure skin friction coefficients either directly by a balance system or indirectly from velocity profiles, it was decided that it would be easier and faster to measure turbulence intensities near the plate by use of a hot-wire anemometer. The reasoning was that, by Von Kármán's similarity hypothesis, the turbulence shear stress distribution in a boundary layer is proportional to the turbulence kinetic energy and hence proportional to relative turbulence intensity. Any increase or decrease in the relative turbulence intensities in the boundary layer would then be indicative of corresponding increase or decrease in the Reynolds stresses and wall skin friction.

The size and speed of the wind tunnel limited the amount and thickness of a natural turbulent boundary layer on a flat plate. So, in order to overcome this limitation and in order to magnify the effect of flabby skins on turbulence intensities, a small wood fence 9/64 inch high was placed perpendicular to a flat aluminum plate covered by a flexible plastic polyvinyl chloride (PVC) skin (commercial name—"Clopay Frosty") of 0.0025 inch thick. Between the aluminum plate and the flexible skin was a ⅜-inch gap. This gap was filled with either air, water, or automotive lubricating oil (30 wt). The plate was 37 inches long and 6.75 inches wide and was placed in the tunnel lengthwise. The nominal air speed in the wind tunnel was 29 fps.

A hot-wire anemometer (Flow Corporation Model HWB-3) was then used to measure the axial relative turbulence intensities, I, at various axial distances downstream of the fence but at a fixed distance of 9/64 inch above the surface of the flabby skin in the center of the plate. The output of the hot-wire anemometer was fed to either an oscilloscope or a root-mean-square meter.

Figure 1 shows that the amount of turbulent damping is a function of the viscosity of damping fluid. The three coatings tested all showed less turbulence than the hard surface, and the turbulent damping increased as the viscosity of the damping fluid increased. Intuitively it was felt that this trend must certainly reverse itself if the damping fluid viscosities were to be increased to some larger value. As the viscosity approaches infinity it would seem reasonable to expect the coating to then behave as a hard surface.

These tests were only exploratory, but they were encouraging in that the flabby skin did reduce the turbulent intensity, and they led us to speculate that perhaps the skin friction was also reduced by these coatings.

Skin Friction Tests

A preliminary analysis using the Von Kármán similarity hypothesis showed that the following correlation between skin friction and turbulence intensity might exist,

$$(C_{f_f} - C'_f)/(C''_f - C'_f) = (I_f/I_{hp})^2 \quad (1)$$

where C_{f_f} is the local skin-friction coefficient of flexible wall; C''_f and C'_f are the local turbulent and laminar skin-friction coefficients of the hard plate, respectively; and I_f and I_{hp} are the turbulence intensities of the flexible wall and the hard plate, respectively.

It was intended to see if such a skin-friction reduction could, in fact, be detected for air in a wind tunnel. The open-circuit wind tunnel was modified for this study and had a test section of 20 × 13 × 48 inches,

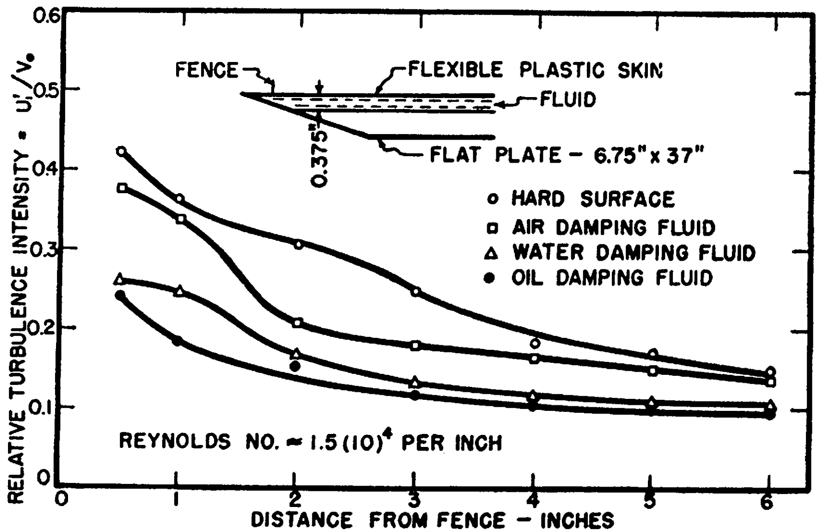

Figure 1. Variation of relative turbulence intensity.

with a test section velocity of 38 fps. The cross-section area increased slightly in the downstream direction to cancel the decrease in effective flow area because of boundary-layer displacement growth. The axial pressure gradient was less than 0.00021 psi/in.

The skin friction was measured on a floating panel flush with the floor of the tunnel (see Figs. 2 and 3). The floating panel was comprised of an aluminum plate plus wood edge rails, 5/16 inch high, to hold the damping fluid in a 25⅛ inches long by 7⅛ inches wide area. This test plate was covered with the plastic PVC membrane. The four outer sup-

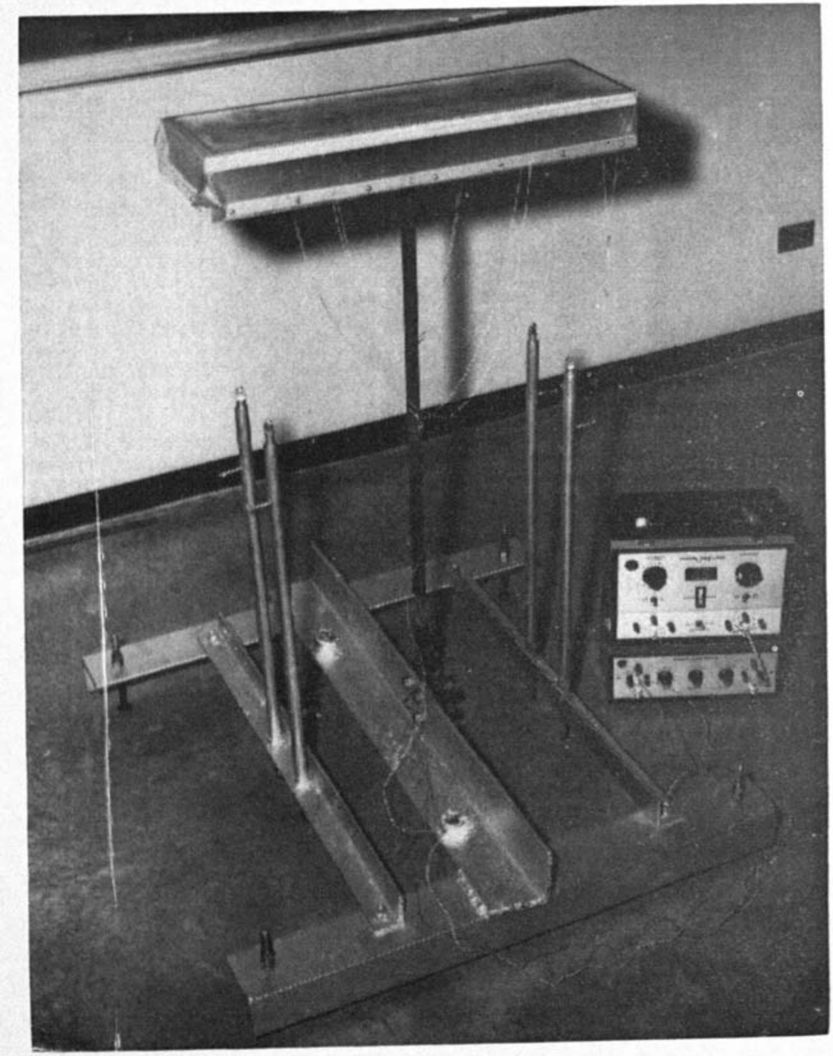

Figure 2. Test plate

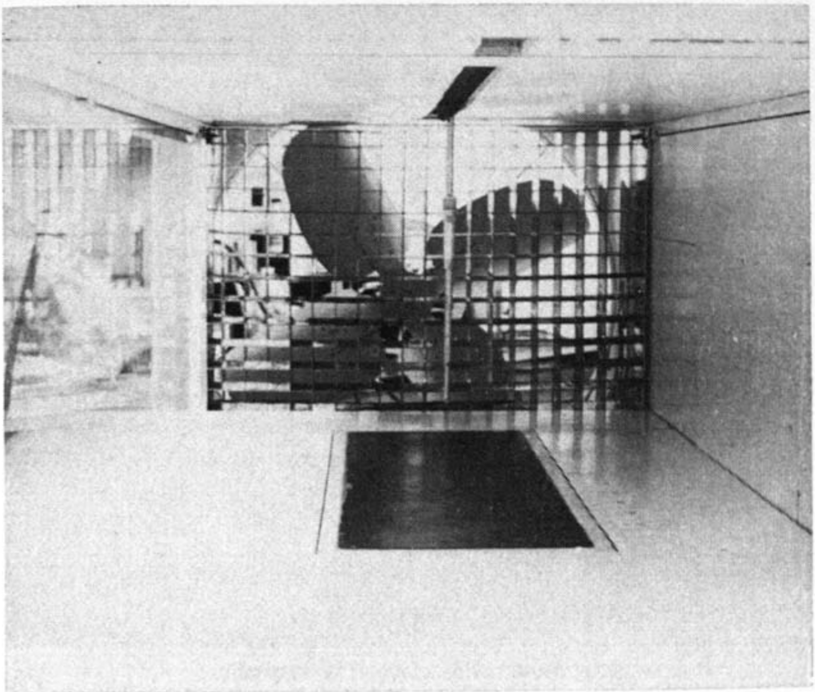

Figure 3. Front view of test plate in wind tunnel test section

ports are lowered during a run leaving the center bar as the only means of support. The reservoir was filled with various fluids of different viscosities, and then a sheet of PVC (0.0035 or 0.0025 inch thick) was stretched across it. The damping fluids used were air, water, and solutions of water and Polyox (polyethylene oxide, WSH-301, Union Carbide Co), which is a water-soluble resin with a molecular weight of 4×10^6. The PVC (from Hooker Chemical Corp.) had a Young's Modulus of only 1400 psi. The skin was cut so that approximately 3 inches would hang over each side of the test plate. Two wood strips were clamped on the outer edge of each of the four sides of the skin. Fastened to each wood strip by a wire was a weight retainer in which various known weights could be placed, so that the tension on the skin could be varied in both the longitudinal (x) and lateral (z) directions. When the membrane was in position over the reservoir and under tension, there was approximately a 1/16-inch gap between its edges and the edges of the wind-tunnel floor. Hard-plate C_F's were obtained by inserting a hardwood plate into the reservoir and covering it with a 0.0035-inch PVC sheet.

The skin-friction force measuring system consisted of a vertical cantilever beam of 1-inch $\times$ ½-in. aluminum and highly sensitive semiconductor strain gages. The strain gages measured the skin-friction force on the top of the test plate, which being perpendicular to the aluminum bar caused a bending moment along the beam. A large plastic bag was sealed under the wind tunnel and measuring system to keep air from entering the slots around the test plate (see Fig. 4).

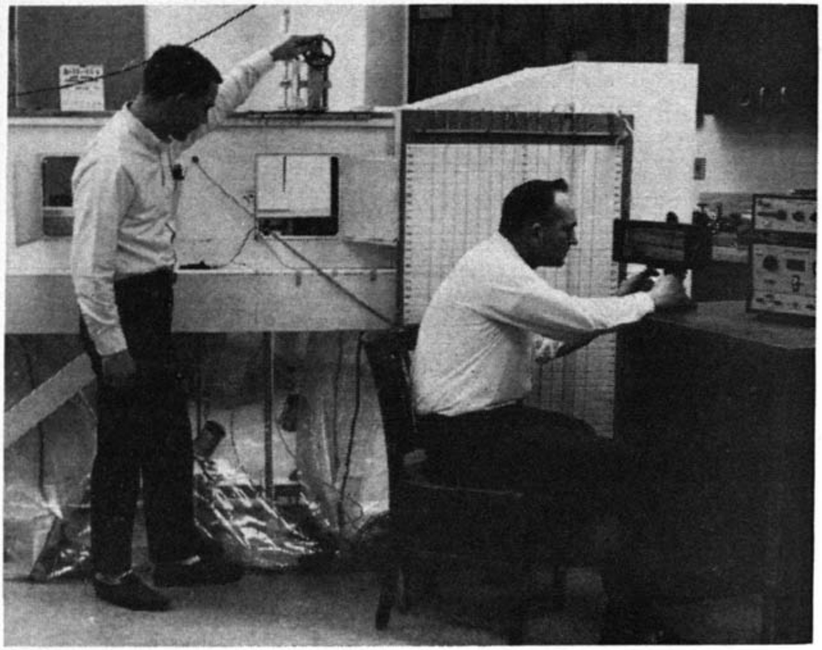

Figure 4. Side view of wind tunnel

The measured hard-plate skin-friction coefficients were 0.00373 for a T_x = 0.049 lb/inch, T_z = 0.085 lb/inch, and 0.00379 for a T_x = 0.049 lb/inch, T_z = 0.269 lb/inch. The slight difference in the two C_F values is not considered due to change in tension but due to the scatter in the data. A theoretical C_F of 0.00398 was calculated by integrating the local turbulent skin-friction equation

$$C_f = 0.0576(U_1 x/\nu)^{-1/5} \qquad (2)$$

over the flat plate. This good agreement indicated that the boundary layer was turbulent. Moreover, using a hot-wire anemometer, it was found that the velocity profile followed closely the 1/7th power law velocity distribution (see Fig. 5).

Thus assured that the flow was turbulent and that the reference base line was within acceptable accuracy, the first experiment was conducted using water as the damping medium and a 0.0035-inch PVC membrane. The results (Fig. 6a) indicate the C_F has been reduced as much as 40% from the hard plate reference. In general, for T_x < 0.4 lb/inch, C_F decreases with an increase in T_z, whereas the slope indicates a decrease in C_F with an increasing T_z. However, at the higher T_x values, the curves tend to merge, the slopes approach zero, and there is less significant separation with a variance in T_x or T_z. The experimental uncertainty of the C_F measurements was estimated to be approximately ± 0.0002 (or 5%). T_x was varied out initially to 0.638 lb/inch but the flexible skin stretched and formed permanent wrinkles, so that subsequent tests were restricted to 0.4 lb/inch.

In the second test (0.0025-inch PVC, Fig. 6b), the slope did not indicate any significant change in C_F with increasing T_z. It is hard to state

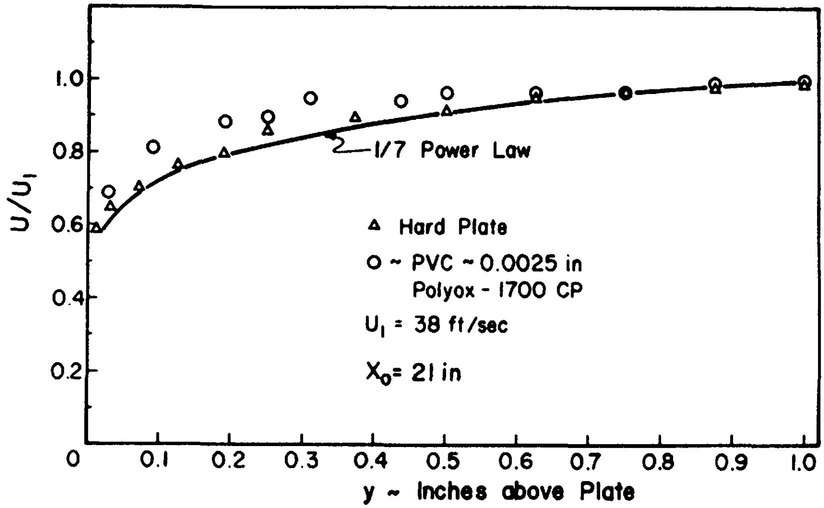

Figure 5. Velocity profiles for flat plate

the exact effect of T_s on C_F, but again there is a definite decrease in C_F relative to the hard plate, and a greater reduction than with the thicker skin.

The next experiment was conducted with air as the damping medium (Fig. 6c). The oscillations of the strain indicator meter during these tests made it very difficult to read the average deflection point on the strain indicator; it was necessary to repeat a test point many times and average the readings. Again, C_F values are considerably lower than hard plate data and independent of T_s. However, the lowest C_F is associated with the lower T_s value, in contrast to Figs. 2a and 2b.

For the lower-viscosity Polyox solution (Fig. 6d), the C_F values at the lower T_s's are normally higher than water and comparable to air; but as T_s increases, the C_F values approach those of water or of air for a given $T_s = 0.088$ lb/inch. As T_s increased from 0.049 to 0.088 lb/inch, C_F decreased, similar to Fig. 2c. The experiment with the high-viscosity Polyox solution (Fig. 6e) was an attempt to locate the viscosity where C_F values would begin approaching hard-plate data. Apparently, this point is at a still higher viscosity, since the data still indicate 40-50% reduction in C_F. The C_F values are essentially constant as T_s increases, but the lowest C_F occurred at $T_s = 0.088$ lb/inch.

In general, flexible boundaries seem to reduce skin friction in turbulent flow by as much as 40-50% in some configurations. The data suggest that C_F is a complex function of longitudinal tension, lateral tension, viscosity (or kinematic viscosity), and either skin thickness and/or skin mass per unit area. Most of the data indicated there was a drop in C_F as T_x was increased from 0.023 to 0.392 lb/inch. The thinner skin (0.0025 inch) performed better than the thicker skin (0.0035 inch) with water as the damping fluid. No trend was discernible in the effect of lateral tension (T_s) or viscosity on C_F. If the magnitudes of T_s and viscosities were increased, perhaps a trend would emerge. Other variables that should be investigated in future experiments are velocity or Reynolds number, length and width of test plate, depth of the reservoir, and Young's modulus of the skin.

Hot-wire, Anemometer Experiments

Concurrent with the skin friction tests, experimental measurements were made with the hot-wire anemometer. The hot-wire anemometer was used to measure Reynolds stresses and turbulence intensity. Figs. 7 and 8 are plots of Reynolds stresses measured with an X-probe in the boundary

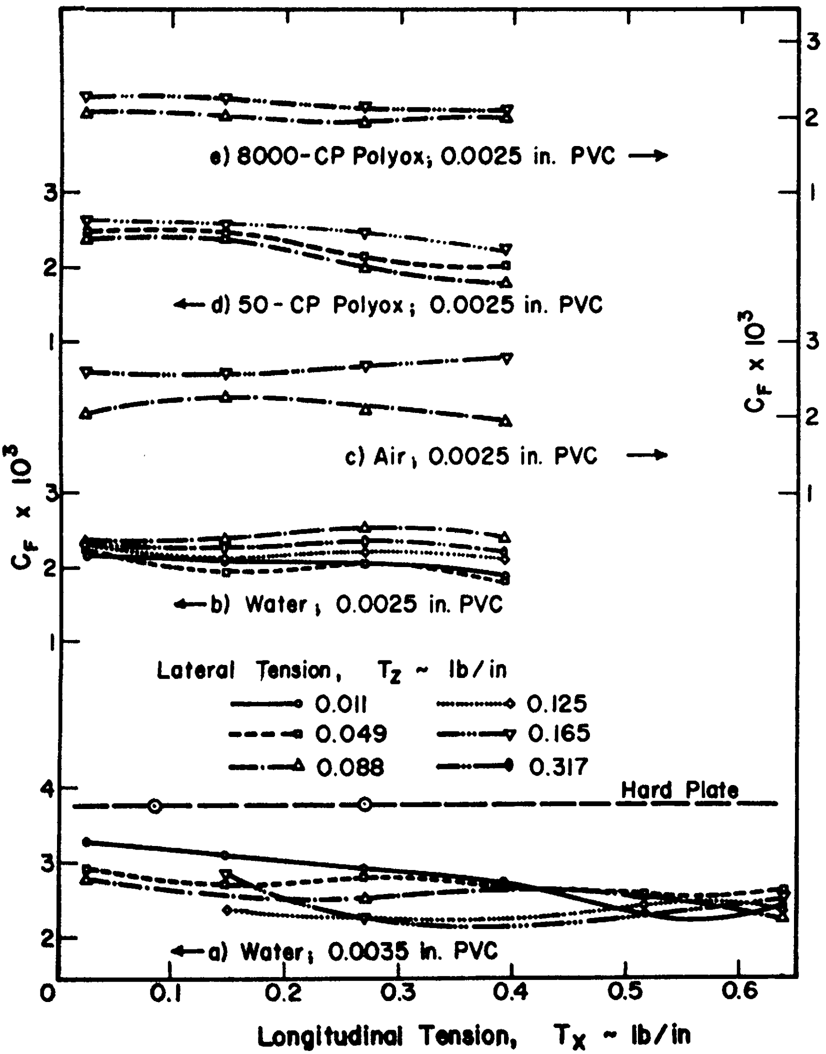

Figure 6. Skin-friction coefficients for various damping fluids and polyvinyl chloride skins

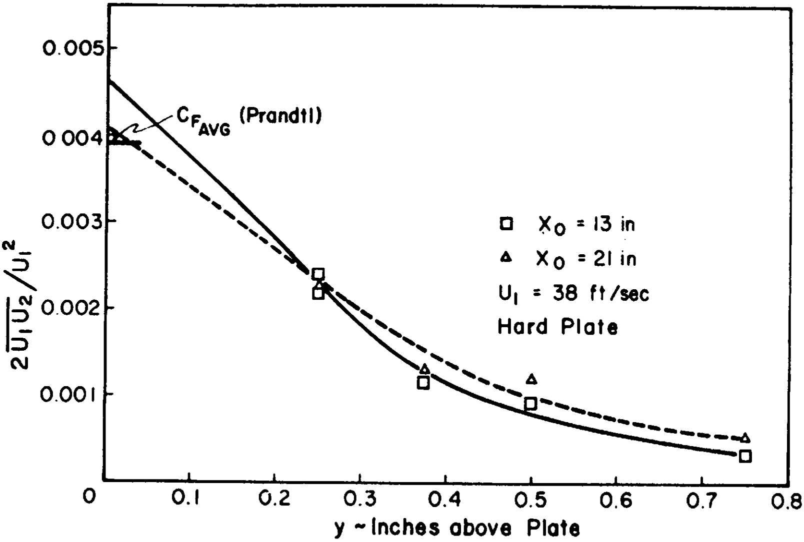

Figure 7. Distribution of Reynolds stress on hard plate

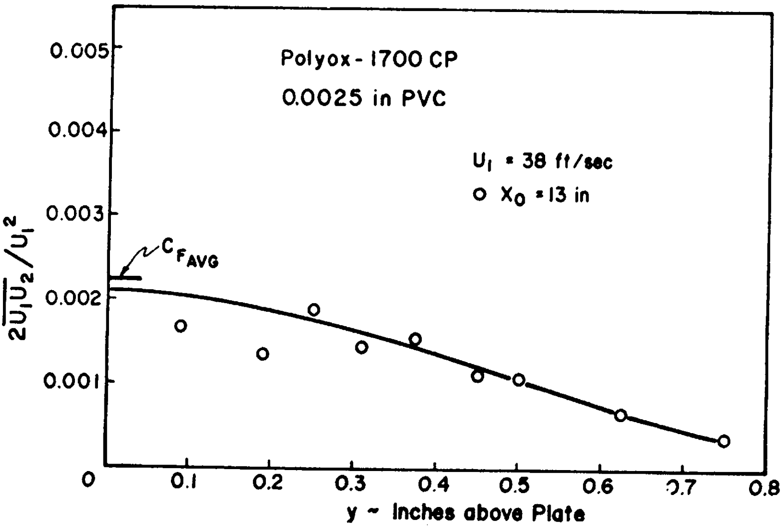

Figure 8. Distribution of Reynolds stress on compliant coating (0.0025" PVC)

layer. The physical size of the X-probe limits the distance one can get near the wall. The data has been extrapolated to the wall in each figure in an attempt to get an indication of the wall shear stress. This extrapolation is based upon well known experimental evidence that the total shear stress in a turbulent boundary layer is approximately equal to the Reynolds stress except in the thin viscous sublayer. The accuracy of the extrapolations is limited by the scatter of data and lack of data near the wall but it appears obvious that the flexible plate has lower Reynolds stresses than the hard plate. In addition to the skin friction coefficient obtained from the Reynolds stresses in Fig. 8, near the middle of the plate ($X_o = 13$), appears to correlate closely with measured value of the average coefficient.

Figs. 5 and 9 are plots of the velocity profiles on both the hard and flexible plates. The hard plate data appear to fit the 1/7 power law in Fig. 5 and the standard "Law of the Wall" equation in Fig. 9. The flexible wall data in Fig. 9 are parallel to the hard plate data which indicate that the Prandtl mixing length is the same for both hard and flexible plates. In addition it appears that there is an increase in the laminar sublayer thickness of the flexible plate, if one assumes "a priori" that the laminar sublayer for the flexible plate follows the same equation as the hard plate ($U^* = Y^*$).

Turbulence intensity measurements made along the length of the plate are shown in Fig. 10. With the exception of the air data the flabby skin damped out the turbulence intensity better than the hard plate.

Fig. 11 represents an attempt to verify experimentally the skin friction-turbulence intensity relation predicted by Eq. (1). It should be noted that while Eq. (1) shows a relationship between local skin friction and local turbulence intensity, Fig. 11 is a plot of average skin friction versus average turbulence intensity. Average values were used in Fig. 11 because no experimental local skin friction coefficient data were available. It is obvious from Fig. 11 that there is scatter of the data and the correlation between skin friction reduction and turbulence intensity reduction is only fair.

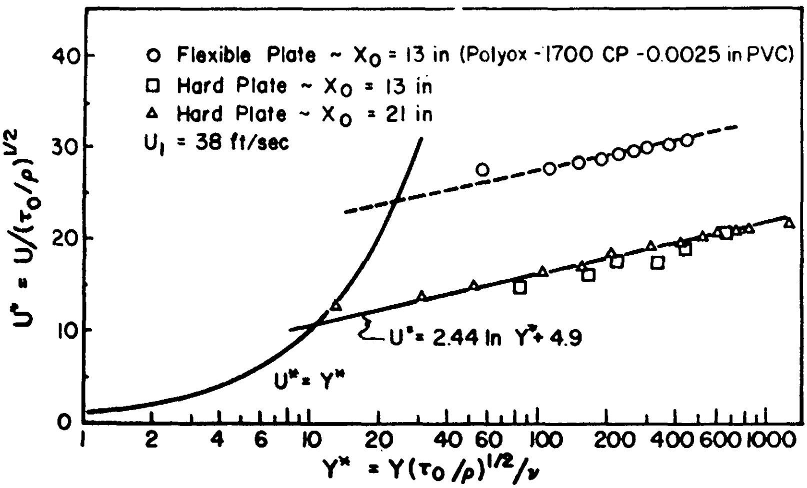

Figure 9. Universal velocity profiles

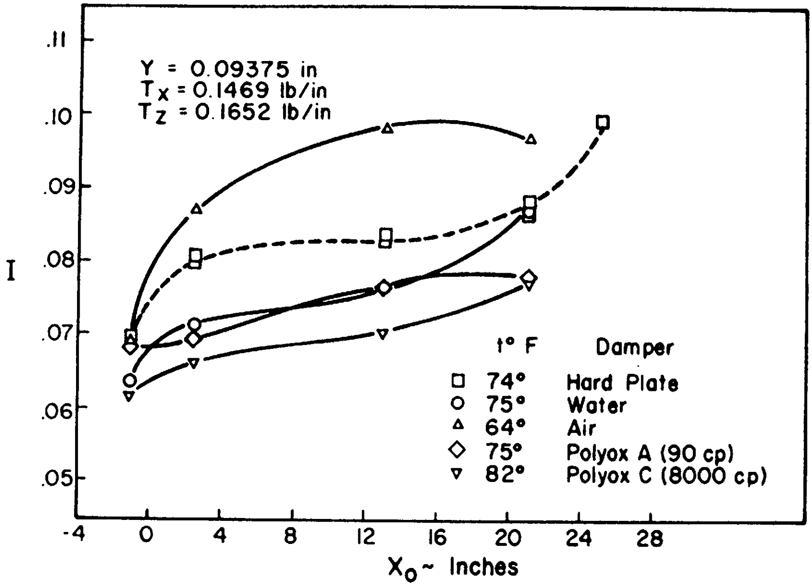

Figure 10. Turbulence intensities for various damping fluids (0.0025" PVC)

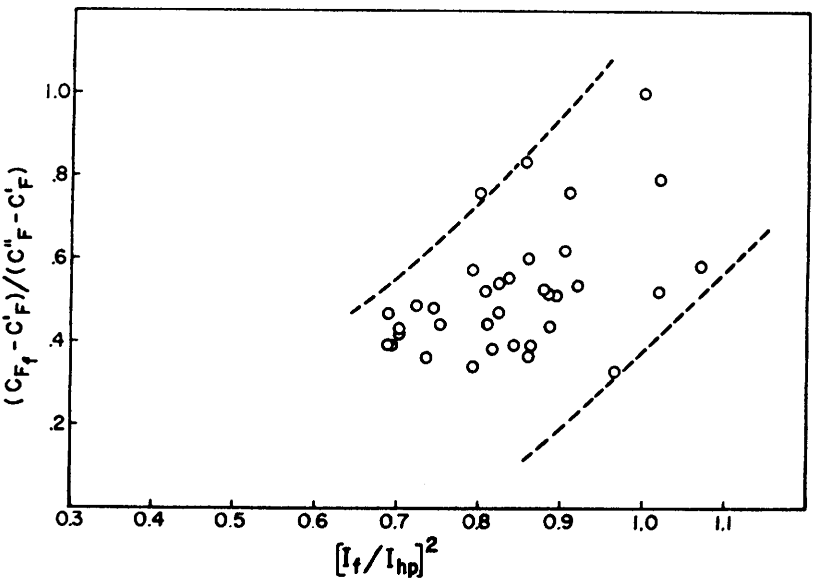

Figure 11. Skin friction-turbulence intensity correlation

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