Engineering Notes

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Skin Friction of Compliant Surfaces with Foamed Material Substrate

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Introduction

IN the last ten years, many investigators have worked toward the goal of skin-friction drag reduction by the use of compliant coatings. The results have been mixed and often unpromising. An encouraging beginning was made by Kramer,[1,2] who reported a drag reduction on streamlined bodies towed in water, the bodies being coated with a compliant skin. Kramer's compliant coating was modeled after the dolphin's skin, which Kramer held responsible for the high swimming speed of the dolphin. The dolphin's skin is believed to absorb and dissipate oscillatory energy from the boundary layer, thus retarding transition and extending the laminar flow to a larger area of the dolphin's body than would be experienced by a similar body with rigid surface.[3]

Following Kramer's work, many experimenters with compliant coatings have been unable to measure a significant reduction in skin-friction drag. Ritter and Messum,[4] in turbulent-flow water tunnel tests of several flexible coatings, found one coating (constructed of soft rubber) which indicated a drag reduction of approximately 10%, but data scatter made the results unreliable. Karplus[5] found that the onset of turbulence occurred farther upstream for a flexible wall, but the degree of turbulence grew to its final value more slowly than for the rigid wall. These tests were conducted for water flowing over stretched mylar film backed by various damping fluids. Lauffer and Maestrello[6] tested fifteen different combinations of steel, aluminum, mylar, and fabric skins with rubber and aluminum rib supports. These compliant surfaces were tested in turbulent airflow in channels; no significant skin-friction reduction was found. A similar lack of success was reported by Gregory and Love,[7] Smith,[8] Benjamin,[9] and Stephens.[10]

On the other hand, successful experiments were reported in Refs. 11–15. Von Winkel and Barger[11] measured a significant reduction in the intensity of fluctuations of the surface pressure on a flexible skin, as compared to a rigid surface. Fisher and Blick[12] found that the turbulent intensity in the boundary layer of a compliant surface was appreciably less than for a hard surface. Walters and Blick[13] confirmed and extended the experiments of Fisher and Blick. Pelt[14] reported that reductions as great as 35% in skin friction for flow in pipes was achieved by lining the interior of the pipe with a flexible tube. The annular space between flexible tube and rigid pipe was filled with damping fluid (air, water, or glucose). Looney and Blick[15] measured large decreases in the skin-friction coefficient of a flat plate in turbulent air flow. A flat plate with a compliant surface was formed by stretching a sheet of 0.0035- or 0.0025-in.-thick polyvinyl chloride (PVC) over a $\frac{5}{16}$-in.-deep reservoir filled with air, water, or solutions of water and polyethylene oxide. The latter two damping fluids yielded better results than did the air. The authors' intent was to extend the results of Looney and Blick to a more durable compliant surface than a thin membrane backed by a liquid.

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Experimental Equipment

The open-flow wind tunnel used in this investigation is the same one used by Looney and Blick,[15] and is described in detail in Ref. 16 and briefly in Ref. 13. The tunnel test section is 48 in. long by 20 in. wide by 13 in. high. Operating speed is constant at 38 fps, and the tunnel ceiling may be adjusted to maintain constant effective flow area as the boundary layer thickens in the downstream direction. This allows the maintenance of a near-zero pressure gradient in the test section. Pressure taps distributed along the test plate were monitored during the test runs, and the pressure gradient along the plate was not allowed to exceed 5.7×10^{-7} psi/in., which represents a drag error of 2% of the skin-friction drag of the rigid (baseline) surface.

The compliant surface test specimens were mounted on a floating aluminum plate so that the compliant surface was flush with the tunnel floor. The test surfaces were 26.1 in. long by 8.1 in. wide. The gap between the edges of the test plate and the tunnel floor was approximately $\frac{1}{16}$ in., yielding a gap-area-to-test-plate-area ratio of approximately 2%. The test apparatus used in Ref. 17, which reports the results of a systematic investigation of errors involved in the measurement of skin-friction drag by means of a floating plate, also had a gap-area ratio of about 2%. Airflow through the gap around the test plate was prevented by the installation under the tunnel of a large plastic bag containing the test plate and its support stand, and sealed to the underside of the tunnel (see Fig. 1).

The method of aquisition of skin-friction data was modified somewhat from that of Looney and Blick. The strain-gaged support for the test plate was used only as a null indicator, rather than as a direct indicator of skin-friction drag. This was done to insure that the test plate had a minimum angle of incidence to the airflow as the data were taken. For each test run, the air-off position of the strain-gage indicator was noted. Then with the tunnel airflow established, the strain indicator was returned to this null position by attaching

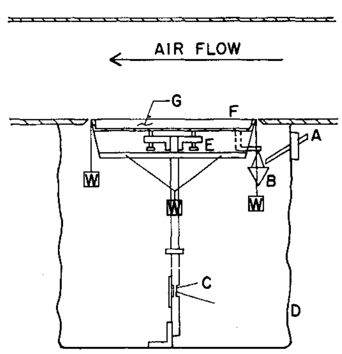

Fig. 1 Schematic of skin-friction balance system. A—tube for inserting balls, B—cup for holding balls, C—strain gage, D—plastic vacuum-sealed enclosure, E—fine adjustment, F—PVC skin, G—substrate, W—weight to apply tension to PVC skin.

Table 1 Properties of the polyvinyl chloride skin[a]

Density	78.6 lb/ft^3
Thickness	0.0025 in.
Tensile strength	2500 psi
Modulus of elasticity	643 psi
Ultimate elongation	240%

[a] Data provided by Hooker Chemical Co., Hicksville, N.Y.

weights to the test plate. The weights used were identical steel ball bearings weighing 2.044 g each. These ball bearings were placed singly in a cup fastened to the test plate. Since the moment-arm distance at which the weights were added was known, the skin-friction coefficient was readily calculated. To improve the reliability of the data, each test point was repeated five times and the results averaged.

Compliant Surface Test Specimens

Four different resilient materials, plus the rigid surface baseline, were used. Each of these materials was tested bare, and also with a covering of 0.0025-in.-thick polyvinyl chloride (PVC) like that used by Looney and Blick.[15] Finally, each material was tested in a water-saturated condition with the PVC skin. The 27 pores/in. polyurethane foam test specimen with its PVC skin beside it is shown in Fig. 2. After installation, 0.10 lb/in. tension was applied to the PVC skin by means of weights.

Each specimen of foam was edged with rigid, vertical sideboards. These sideboards prevent rounding of the shoulders of the test material when tension is applied to the PVC skin, and also retain water for the water-saturated tests. For these latter tests, the water level was maintained such that the resilient material was actually standing in water, and the PVC skin was in contact with the water.

Pertinent properties of the polyvinyl chloride skin and the resilient materials are presented in Tables 1 and 2. The "compression modulus" listed in Table 2 was calculated according to the relation

$$\text{compression modulus} = \frac{\text{force applied/area}}{\text{deflection/initial thickness}}$$

The same force was applied, over an identical area, to each test specimen of resiliant material. The area over which the force was applied was small compared to the area of the test specimen. The test materials were of different thicknesses; these thicknesses are given in Table 2. The deflection of the wet 40-PPI polyurethane foam under the compressive test load was more than 75% of its initial thickness; the deflection of the other materials was 50% or less. The compression

Table 2 Properties of the resilient test materials

Material	Thickness, in.	Density, lb/ft^3	Compression modulus, psi: Dry	Compression modulus, psi: Wet
27-PPI[a] polyurethane foam (Scott Paper Co., Chester, Pa.)	$\frac{31}{32}$	1.6	3.80	1.61
40-PPI polyurethane foam (Precision Rubber & Plastic Co., Okla. City, Okla.)	$\frac{5}{32}$	1.8	0.97	0.81
80-PPI polyurethane foam (Scott Paper Co., Chester, Pa.)	$\frac{15}{16}$	1.7	2.52	1.19
Foam rubber (Industrial Gasket Co., Okla. City, Okla.)	$\frac{5}{8}$	7.6	7.93	3.19

[a] PPI = pores/in.

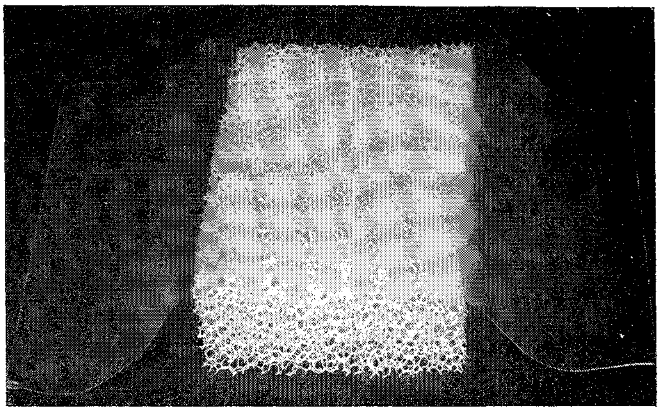

Fig. 2 27-PPI polyurethane foam specimen with 0.0025-in. PVC skin.

modulus of the resilient test materials was reduced by more than 50% when the materials were water saturated, except for the 40-PPI polyurethane, which experienced a 17% decrease.

Results

Measured turbulent-flow skin-friction drag coefficients are shown in Table 3. The wind tunnel was operated at a fixed velocity of 38 fps. The Reynolds number at the upstream edge of the test plate (which was mounted flush with the tunnel floor) was 5.5×10^5, whereas the Reynolds number at the downstream edge was 10.5×10^5. The Reynolds number was calculated with the distance from the inlet of the tunnel. Measurements with a hot-wire anemometer assured that the boundary layer was fully turbulent before reaching the test plate.

A rigid surface baseline was provided by a hard, smooth surface (smooth-sanded fiber-board). This surface was tested both bare and covered by polyvinyl chloride skin. The higher value shown in Table 3 for the rigid surface covered by the skin is due to the method at attaching the PVC skin to the hard plate. This was done with high-vacuum grease, which left wrinkles in the skin. Thus, the skin-covered rigid surface was not as smooth as the bare plate.

It is seen in Table 3 that all of the resilient materials tested exhibited higher skin-friction drag than the rigid surface, for the case with no polyvinyl chloride skin. This was not unexpected, considering the roughness of the bare surfaces compared to the smooth, rigid baseline. The foam rubber had the smoothest surface of any of the test materials, but, unfortunately, economic considerations required that it be pieced together from smaller samples (4 in. × 5 in. each). This produced a test specimen with slight ridges at the joints of the 4-in. × 5-in. pieces.

Table 3 Measured turbulent airflow skin-friction coefficients $\times 10^3$

Material	Bare	Covered with PVC skin	Water saturated, covered with PVC skin
Rigid surface	4.31 (±4%)[a]	5.02 (±3%)	...
27-PPI polyurethane foam	12.92 (±5%)	4.43 (±5%)	2.96 (±6%)
40-PPI polyurethane foam	8.85 (±8%)	3.18 (±2%)	2.65 (±8%)
80-PPI polyurethane foam	7.35 (±0.8%)	2.87 (±6%)	3.37 (±10%)
Foam rubber	5.41 (±2%)	7.39 (±6%)	8.85 (±4%)

[a] Percent of data scatter is in parentheses.

When covered with the polyvinyl chloride skin, the 40-PPI polyurethane foam and the 80-PPI polyurethane foam showed appreciable reductions in skin-friction drag compared to the rigid surface. However, the Scott 27-PPI polyurethane foam experienced a slight increase, and the foam rubber a large increase. The authors can offer no confident explanation for the large increase in drag for the foam rubber with PVC skin. The answer may lie in the previously discussed joint ridges of the foam rubber specimen, but no specific mechanism is apparent.

For the tests with the resilient material saturated with water and covered with PVC skin, the first three materials demonstrated a significant reduction in skin-friction coefficient, while the foam rubber again showed an increase.

An attempt was made to plot the skin-friction coefficients from Table 2 with the compression modulus of Table 2; however the scatter of the data was such that no conclusive trend was observed.

Conclusions

Appreciable reductions in flat-plate turbulent airflow skin-friction coefficient have been demonstrated for somewhat more durable and practical compliant surfaces that those tested by Looney and Blick[15]: 0.0025-in.-thick polyvinyl chloride skin backed by a resilient polyurethane foam either wet or dry. Since the skin was stretched over the foam rather than being bonded to the foam, it is possible that the very thin layer of air or water between the skin and the foam had some effect on the skin friction. In any case, the foam is a more convenient device to contain the damping fluid that an unstructured reservoir, especially if a liquid is used.

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Utilization of Satellite Navigation Techniques in Marine Operations

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1. Introduction

ELECTRONIC aids to navigation are currently used in many marine applications. The shore-based electronic navigation aids, such as Decca, Loran A and C, and Omega, have proven generally satisfactory in locations where adequate system signal coverage is provided. These regions of useful coverage range from approximately 250 to 1000 miles from the shore stations(s) for Decca and Loran, up to 5000 miles for Omega. None of these systems, however, provides the optimum performance combination of worldwide coverage, all-weather operation, and precise position-location capability. All of the aforementioned systems have performance limitations attributable to propagation anomalies and high path attenuation typical of earth-based systems operating beyond the radio horizon.

The Navy Navigation Satellite System (NNSS), operational since 1964, now provided a relatively simple means of position location and navigational data, without geographical coverage or weather limitations. System accuracy is satisfactory for the majority of oceanographic and marine exploration operations. Typically, position errors of about 0.1 naut mile have been experienced consistently.

Satellite navigation system implementation requirements are relatively modest from the user equipment point of view. Until fairly recently, the NNSS requirement for a small, general-purpose shipboard computer to provide real-time readout of position in latitude and longitude had been regarded as relatively costly compared with conventional electronic navigation aid equipments. However, the availability of quite adequate computers costing less than \$10,000 coupled with the ability to automate fully the total navigation problem provided by the computer has resulted in rapid acceptance of the satellite navigation concept on a purely economic basis by both military and commercial/scientific users.

Currently, ITT Aerospace is supplying the shipboard satellite navigation user equipment for the Navy, as the AN/SRN-9. Several commercial versions of this equipment are also being supplied to oceanographic and marine exploration interests.

2. System Operation

The basic NNSS configuration is shown in Fig. 1. Polar orbiting satellites with an orbital period of about 108 min provide full earth coverage. The frequency of position fix availability is determined by the number of satellites in use,

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