Engineering Notes

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Re-examination of Compliant Wall Experiments in Air with Water Substrates

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Introduction

THE original idea of drag reduction using compliant walls is credited to Kramer.[1,2] Kramer's experiments, based on his observations of dolphins, showed drag reductions of approximately 50% for a compliant wall cylinder towed in Long Beach Harbor. There are currently over 300 experimental data points in the literature which show apparently successful compliant wall drag reductions from 5 to 64%. Currently a coordinated analytical and experimental study[3-5] is being conducted to evaluate compliant walls as a potential turbulent skin friction reduction concept for subsonic aircraft. As part of this study, available data are being carefully re-examined to ascertain their applicability and validity. The purpose of this Note is to present a possible alternative explanation for apparent compliant wall drag reductions measured in previous investigations.[6-8] The results from these investigations are important because they represent a large portion of the compliant wall data which show drag reductions to 50% and because an understanding of these experiments is critical in determining the mechanism responsible for the compliant wall drag reduction.

Skin friction drag measurements are presented in Refs. 6-8 for compliant surfaces in air with foam and/or fluid substrates. These experiments measured directly the skin friction drag on floating panel models which were mounted flush with the subsonic tunnel floor. The models, shown schematically in Fig. 1, were mounted on a long, vertical, single-column beam. Weights were attached to the upstream portion of the models to counterbalance bending moments caused by the surface skin friction. This arrangement permitted very low drag forces to be measured on the compliant model panels (e.g., forces as low as ½% of the hard plate drag[6,7] could be differentiated).

The models[6,7] had a compliant surface 63.8-cm long by 18.1-cm wide whereas the model surface for Ref. 8 was 38.1-cm long by 24.1-cm wide. Various fluid substrates with different viscosities (i.e., air, water, and solutions of water and Polyox) were explored[6,7] at a freestream velocity of 11.6 m/sec. Skin friction drag reductions up to 50% were reported for these tests. Reference 8 explored the effects of freestream velocity (i.e., $U_\infty \simeq 5.2$-67.1 m/sec) on the compliant wall drag reduction for porous polyurethane foam substrates (some of which were saturated with water), and drag reductions up to 38% were achieved. Both investigations used thin polyvinyl chloride (PVC) sheets, either 0.0064 cm or 0.0089 cm thick, for the compliant wall skins.

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Analysis and Discussion

The present analysis stems from thus-far unsuccessful attempts to experimentally verify these earlier experiments. No drag reductions were obtained in the recent experiments which were conducted in a small subsonic wind tunnel on floating panel compliant wall models with liquid substrates. The size of the models tested, the fluid substrates, and the flow conditions were similar to those reported in Refs. 6-8. The major difference between the current experiments and those conducted earlier was the method of obtaining the direct skin friction drag measurements. Whereas previous experiments[6-8] used the single-column, cantilever-beam type of arrangement, the current experiments supported the floating panels by thin wires attached to each of the four corners of the test panels outside the air stream. The drag force was then obtained by determining the amount of weights necessary to null the test plate to the original wind-off position. Although it is not the intent of this Note to discuss the details of these drag force experiments, the results suggest a possible explanation for the large apparent drag reductions obtained previously with compliant walls (with liquid substrates).[6-8]

In the present attempts to duplicate the earlier experiments, standing waves were observed to form on the compliant surface as the freestream velocity was increased from 15 m/sec to 30 m/sec. These waves resembled sine waves with half of the wave protuding over the upstream portion of the model and the other half of the wave being recessed over the downstream end of the model. Reference 8 and private communications with E. F. Blick of the University of Oklahoma achnowledge the existence of small standing waves in their tests at certain freestream velocities. This information coupled with the results of the recent drag reduction experiments suggest that standing waves in the earlier experiments could have caused a shift in the model center of gravity creating a bending moment that was interpreted as a reduction in the skin friction drag.

An analysis was made to determine the amplitude of a simple sine wave that could produce a center of gravity shift and resulting bending moment large enough to account for an apparent 40% reduction in skin friction drag on a single-beam balance. The assumed wave shape is shown in Fig. 1. Based on a hard plate average skin friction coefficient of 0.00389 for the tests of Refs. 6-7, the apparent drag reduction is approximately 1.9 grams. For the balance moment arm of 85.7 cm,[6,7] this apparent drag reduction would generate a bending moment of 1.63 gm-m. The maximum amplitude of a sine wave necessary to shift the model center of gravity upstream and to create this bending moment is only 0.013 cm (assuming that the compliant wall skin is always in contact with the water substrate). Obviously surface motion this small would be very difficult to detect with the unaided eye and could have been overlooked previously.

To determine the magnitude of the possible surface deflections, surface motion measurements were obtained in the present study on a compliant wall model with 0.0064 cm thick PVC skin stretched over a water-filled cavity. These tests were representative of those in Refs. 6 and 7. The model had a compliant surface 76.2-cm long by 20.3-cm wide and was tested at a freestream velocity of 16.2 m/sec. Uniform tension ($\simeq 3.5$ N/m) was applied laterally and longitudinally to the compliant wall membrane with a vacuum-tensioning device. An optical system was used to measure the compliant wall surface motion. The system has two photo detectors, 1.37 cm apart, and is driven on a track over the full length of the model surface. Each photo detector measures the in-

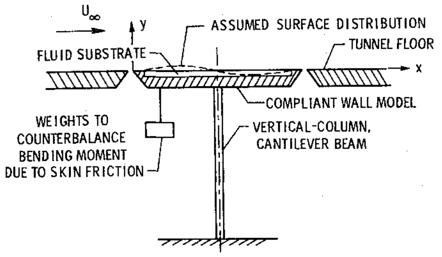

Fig. 1 Simplified schematic of models used in Refs. 6-8.

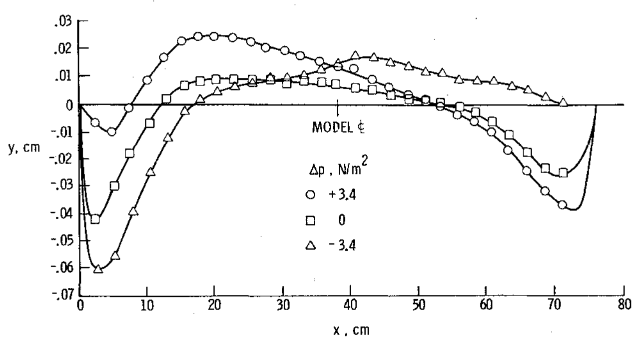

Fig. 2 Surface motion measurements for compliant surface with water substrate.

stantaneous surface angle over a spot 0.13 cm in diameter to within 0.002 of a degree. For the present study, only one detector was used and a time average over a long period of time was used at each x position to determine the average surface angle. The original wind-off surface angles and then the wind-on surface angles were measured, and the differences between the two were integrated to obtain the flow induced change in surface position.

Surface position measurements on the PVC compliant skin model with water-filled substrate are presented in Fig. 2 for three longitudinal pressure gradients. Pressure gradients of these magnitudes were found in Refs. 6-8. References 6 and 7 modified the upper tunnel wall to eliminate or reduce the gradients whereas Ref. 8 corrected the drag measurements by calculating the bending moment induced by the variation in the surface pressures. In the present study, the gradients were obtained by moving the tunnel side walls ± 0.318 cm from the mean zero pressure gradient position. These changes produced a 1.1% variation in the stream velocity with a 2.2% variation in static pressure. The corresponding changes in the static pressure (Δp) over the 76.2 cm long model was approximately ± 3.4 N/m^2.

The large effect of only small pressure gradients on the formation of standing waves on the compliant wall surface is evident from Fig. 2. For the nearly zero pressure gradient the surface protrudes outward by approximately 0.009 cm. The positive gradient creates a bulge over the upstream portion of the model whereas the negative gradient causes the bulge to shift to the downstream portion of the surface. The model fairing plate around the compliant surface causes the surface to dip over the first 7.6-16.5 cm for all three gradients; the surface dips over the last 23 cm for the zero and slightly positive gradients.

The water volume under each of the three waves in Fig. 2 was integrated to determine the bending moment caused by the transfer of the water mass. The slightly positive gradient shifts the center of gravity upstream of the model centerline and generates a 3 gm-m bending moment. The near zero and negative pressure gradients shift the model center of gravity downstream of the model centerline and generate 0.1 gm-m and 3.3 gm-m bending moments, respectively. These bending moments in each situation would be sufficient to significantly alter the drag reductions reported in Refs. 6-8 and hence compromise the validity of the data (e.g., the 3 gm-m bending moment for the positive gradient could have indicated an apparent 70% "drag reduction").

The present analyses and measurements suggest a plausible explanation for previously measured compliant wall drag reductions.[6-8] References 6-8, however, are not the only experiments in the literature to show successful compliant wall drag reductions; a number of experiments (e.g., Refs. 1-5, 9, 10) still exist which support the compliant wall as a possible drag reduction device. The amount of drag reduction that can be obtained with compliant walls, the surface motion required for compliant wall drag reduction, and the mechanism responsible for the drag reduction must be better understood before an evaluation of compliant walls as a potential turbulent skin friction reduction concept for subsonic aircraft is possible.

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Windward Plane of Symmetry Laminar Cross-Flow Effects

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Nomenclature

A = constant in skin friction law [see Eq. (3)]; at zero angle of attack, $A = 0.2205$ for laminar flow, $A = 0.0128$ for turbulent flow
C_f = local skin friction coefficient
f''_w = nondimensional velocity gradient at the body surface
h = static enthalpy
h_2 = length element or scale factor which characterizes spreading of the streamlines
H_e = total enthalpy

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