A Laser Interferometer for Measuring Skin Friction in Three-Dimensional Flows

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Introduction

A NEW, nonintrusive method for measuring skin friction in three-dimensional flows with unknown direction has recently been described by Monson, et al.[1] The method uses a laser interferometer to measure the changing slope of a thin oil film applied to a surface experiencing shear stress. This Note presents the first experimental results in which the method is used to measure skin friction in a well-documented three-dimensional flow.

Principle and Experiment

The new skin-friction method is an extension of the oil viscosity balance method first described by Tanner.[2] In the three-dimensional flow application with unknown direction, two laser beams with known spacing are focused on a surface such that the line between the foci is parallel to the desired measurement direction. Then, a straight line of oil is applied ahead of the front beam orthogonal to the measurement direction. The flow is started, the oil flows downstream past the two beams, and the time rate of change of the oil film's slope is recorded by monitoring the time-dependent optical interference between the reflected light from the oil and substrate surfaces using photodiodes. In turn, this information is used to compute the average skin-friction component. By rotating the laser beam and oil line orientations 90 deg and making a separate test, the skin-friction component orthogonal to the first measurement is obtained, thus giving the total skin-friction vector at that point. A full description of the method, together with the applicable data-reduction equations, are given in Ref. 1.

Verification experiments were conducted in a low-speed wind tunnel which had a cylindrical centerbody extending along its axis. A segment of the cylinder was rotated such that its transverse surface speed equaled the tunnel freestream speed of 37 m/s. This produced a swirling boundary layer which was convected onto a downstream stationary segment where it became three dimensional as it turned through 90 deg and relaxed toward a stream parallel to the tunnel axis. Axial and transverse skin-friction measurements were made at several axial positions on the downstream segment. Previous skin-friction measurements and the same locations and test conditions had been performed by Higuchi and Rubesin[3] using a bidirectional surface-fence gage.

Results and Discussion

Axial skin-friction measurements with the laser interferometer method were first made without the middle cylinder segment spinning. Similar measurements with a surface-fence gage had been made previously by Higuchi and Rubesin.[3] The present measurements served to check the agreement between the two methods in a simple two-dimensional flow before they were compared in the more complex three-dimensional flow. Agreement between the two methods and with a turbulent boundary-layer calculation[3] was excellent.

Before proceeding with skin-friction measurements in a three-dimensional flow, the laser interferometer method was applied to the measurement of a series of off-axis components in the two-dimensional flow without cylinder spin. If this method is correct, it can serve as a verification of the three-dimensional theory, since for any measurement angle ϕ away from the x axis, the result, $C_{f\phi}$, should be equal to $C_{fx} \cos(\phi)$.

The results of several such measurements are shown in Fig. 1 along with the expected cos (ϕ) variation in $C_{f\phi}$. Each data point represents the mean of six measurements at each angle, and the error bars represent twice the standard deviation of the repeated measurements. Within the accuracy of the measurements, they all agree with the expected variation. Using the measured components and their uncertainty at 0 and 80 deg, the computed flow angle is |1 deg| ± 2 deg, which agrees with the known flow angle of 0 deg. In a flow with known direction these results verify the basic assumptions in the theory affecting applications in two- or three-dimensional flows with unknown direction.

The values for a gravity-correction parameter, ϵ_ϕ, are also shown in Fig.1. This parameter indicates the extent to which gravity is influencing the skin-friction measurement; it should be much less than unity for the method to remain accurate.[1] This is achieved at the smaller angles, but by 80 deg the parameter has increased to 0.11. Thus, measurements beyond 80 deg were not attempted.

Verification experiments in a three-dimensional flow were then performed with the center cylinder segment spinning. The two skin-friction components, C_{fx} and C_{fz}, measured at several axial positions, are compared in Fig. 2 with measurements by Higuchi and Rubesin[3] using a bidirectional surface-fence gage, and with a theoretical calculation for the swirling boundary layer.[3] Excellent agreement between the two methods and with the theory is observed for the axial components. The error bars shown are computed as before for the zero-spin data, and comparable accuracy for the axial

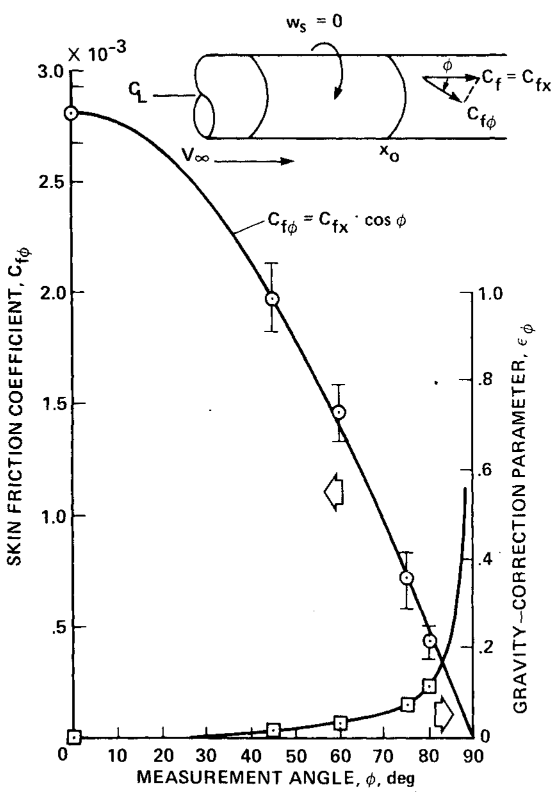

Fig. 1 Measured skin friction vs measurement angle without spin.

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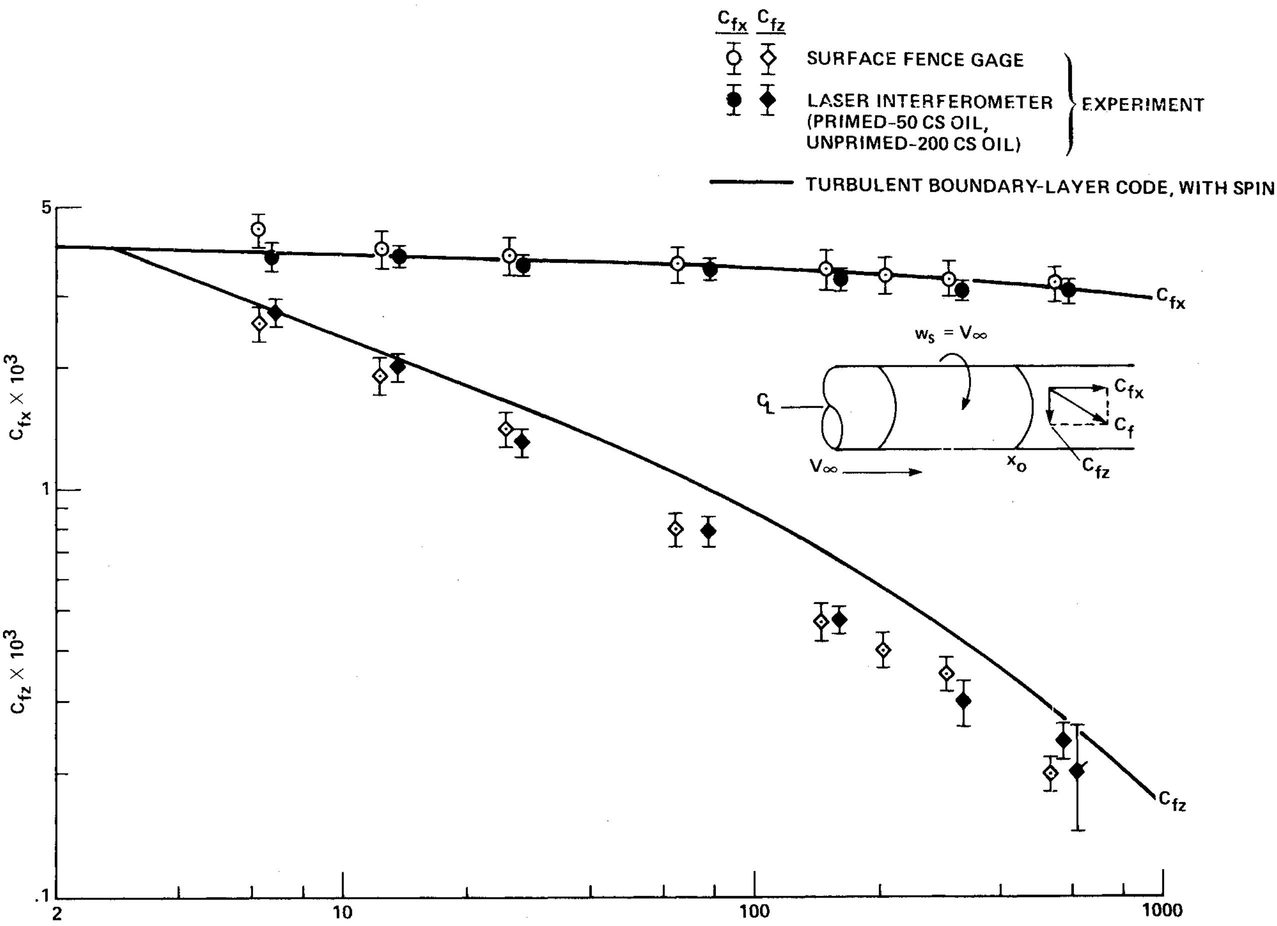

Fig. 2 Comparison of measured and computed skin friction with spin.

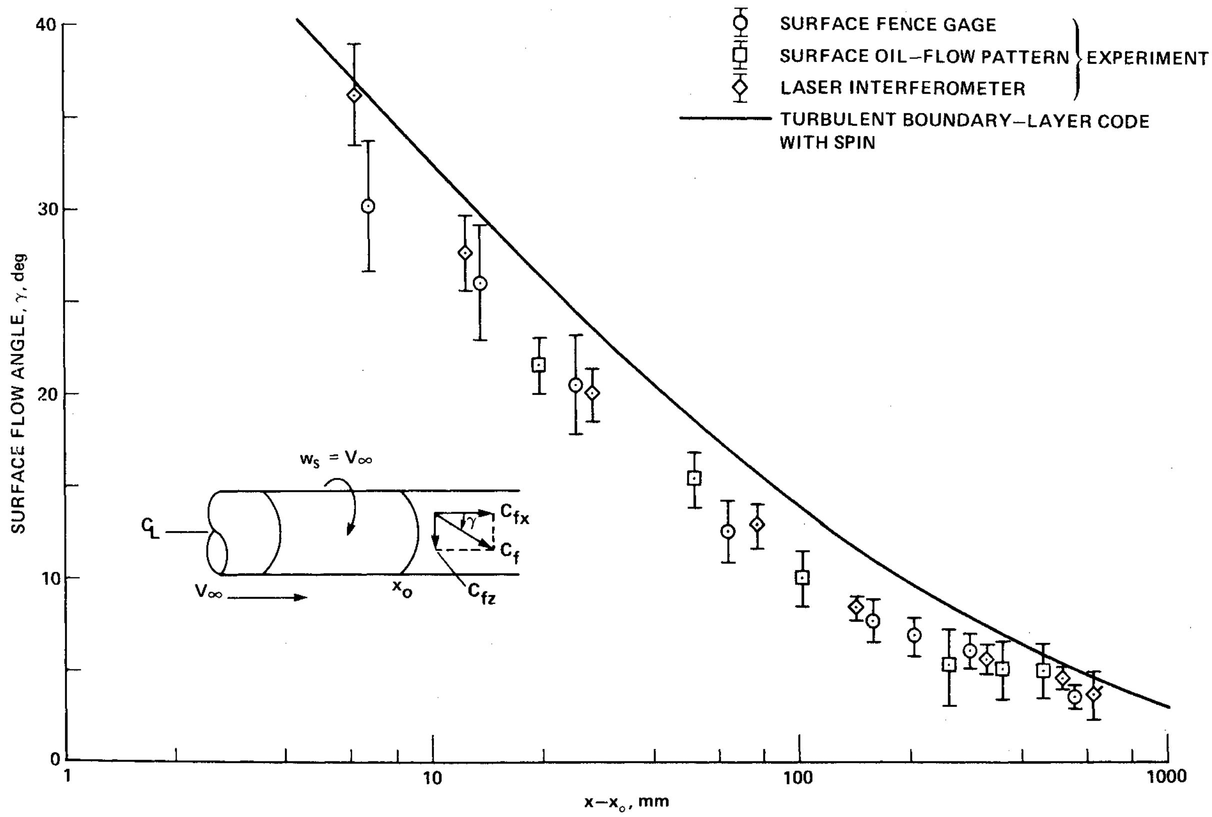

Fig. 3 Comparison of measured and computed surface flow angle with spin.

components is obtained. Except for the last downstream station, excellent agreement between the two methods is also found for the transverse components with the accuracy comparable to the axial data. Agreement with the theory is not as good in the transverse direction, but Higuchi and Rubesin[3] attribute this to limitations in the turbulence model.

At the last downstream station, poorer agreement in the transverse direction between the two methods is observed, and the uncertainty is larger for the laser interferometer data. This can be attributed to three problems that arise with the oil-flow method when measuring transverse skin-friction components nearly perpendicular to the flow direction.

First, since the skin-friction component becomes small, the gravity correction becomes large, and the approximations in the oil-flow theory become less accurate. For example, the gravity correction was 13% at the last station.

Second, small errors in the applied oil-line angle result in large errors in the measured skin friction. For example, when ϕ is 90 deg (a transverse measurement), the error in skin friction is $\delta\phi/\tan\gamma$, which approaches infinity as γ approaches 0 deg for any finite error, $\delta\phi$, in oil-application angle.

Third, the oil-flow path length from the oil leading edge to the downstream beam measurement point becomes large, causing persistent oil surface waves. An attempt was made to reduce the gravity and surface-wave effects at the last station by making measurements with 50-cS oil rather than the normally used 200-cS oil. Although the less viscous 50-cS oil thinned faster and reduced the effects described above, fewer visible fringes were available for the data reduction and thus accuracy was not improved. Consequently, the 3 deg flow angle at this position is probably close to the lower limit for measuring transverse skin friction accurately in three-dimensional flows.

The measured skin-friction components in Fig. 2 may be used to compute the local surface-flow angle γ using $\tan\gamma = C_{fz}/C_{fx}$. The results are compared in Fig. 3 with a theoretical computation and angles measured from surface oil-flow patterns by Higuchi and Rubesin.[3] As expected from the good agreement in Fig. 2, the two skin-friction methods also agree in determining flow angle. Furthermore, they agree with the oil-flow pattern data over the entire range. Note the accuracy of the laser interferometer method even at the last downstream station where there is some error in transverse skin friction. These comparisons lend additional confidence in the skin-friction data previously presented for both methods. On the other hand, the theoretical curve for flow angle in Fig. 3 lies above the measurements over the region tested. This is expected from the previous disagreement found for the transverse skin friction in Fig.2.

Conclusions

The preceding results establish the accuracy and utility of the laser interferometer skin-friction method in three-dimensional flows with unknown direction, at least for flows such as the present one with spanwise similarity. Limitations to the method were found for transverse skin-friction measurements close to the perpendicular to the flow direction, but components outside of 3 deg to the flow normal were measured successfully. In addition, the method is limited to wind tunnels with steady run times of approximately 30 s or longer, in order to accurately measure the flow rate of the oil placed on a test surface.

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Design Sensitivity Analysis Strain Energy via Distribution

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Nomenclature

b, b_m	= vector of design variables and the mth component
$D_{\alpha\beta}$	= compliance tensor
g, g_j	= general form of constraints and its component
G, G_j	= $g = G(b,u)$ [see Eq. (2)]
n_j	= unit vector perpendicular to surface S
N_b	= number of design variables
N_g	= number of constraints
N_ℓ	= number of loading cases necessary to compute displacements
N_p	= number of specified forces
N_r	= total number of redundancies
N_u	= number of displacements in constraint function G
P, P_i	= effective load vector and the ith component
ΔP_i	= increment of P_i
q^r	= reactant component of Q_α
Q_α	= generalized stress
Q_α^w	= free component of Q_α
S	= total surface of a body or structure $= (S_u + S_p)$
S_p	= boundary surface where forces are prescribed
S_u	= boundary surface where displacements are prescribed
u, u_i	= nodal displacement vector and the ith component
U	= total strain energy stored in a loaded system
U_m	= strain energy stored in volume V_m
V	= total volume of an elastic body or structure
V_m	= subset of the total volume V
x_j	= generic point of the reference configuration
γ	= ratio of the computing cost
λ_α^r	= linear function of x_j corresponding to q^r

Introduction

In the present Note, we set out to develop an alternative method for the determination of design sensitivity coefficients of elastic structures based on Castigliano's theorem. The method requires only information on strain energy distribution; hence, it offers an advantage of ease of implementation with an existing finite element program with no modification to the source code.

Three different approaches of computing sensitivity coefficients have been proposed and studied extensively by others.[1-4] They are[5]: 1) the virtual load method (or dummy load method); 2) the state space method; and 3) the design space method.

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