The agreement is good, but the calculated value was 5% lower than that for Churchill's experimental correlation at $Ra = 2500$ (Ref. 7). The difference at a larger Rayleigh number can be attributed to the coarse cells and the first-order finite difference formula. We also calculated the Nusselt number by the second-order finite difference formula, and the heat transfer was estimated to be 14% higher at $Ra = 2500$ than for Churchill's experimental correlation.[7] This also can be attributed to the coarseness of the cells in the y-direction. The convection term is not included in our calculations but this effect may be small around the marginal stability. However, when we take the coarseness of the cells, the results in Fig. 8 satisfactorily show the usefulness of SFD.

Conclusions

We show that the function of the spreadsheet can be extended to CFD by using the iteration function and the circular reference. The present results demonstrate that the cells of the spreadsheet can be used as natural grids for CFD; in addition, we were able to see the computational domain during calculation by coloring the boundary cells.

SFD requires discretized governing equations and boundary conditions and these are reproduced in each cell in a spreadsheet by the copy-and-paste procedure. We then begin iteration and the computation is completed by SFD solution reaching either the specified number of iterations or the specified maximum error tolerance. The procedure was demonstrated for the potential flow over a step using Laplace's equation.

The SFD technique was extended to an inlet flow in a two-dimensional channel, where the Navier–Stokes equations were solved by the spreadsheet and the temperature field also was calculated. The results were compared with those from the laminar inlet flow calculation in order to examine the validity and the usefulness of the method.

The present SFD technique also was applied to a natural convection problem, i.e., to the Rayleigh–Benard instability. The detailed flow and temperature pattern of the Benard cell in an enclosed space with an aspect ratio of 3.2 between two parallel plates were reproduced by means of the spreadsheet computation. The heat transfer estimation was also satisfactory at $Ra = 2500$ (about 5% difference) as compared to the existing experimental correlation.

Although spreadsheets are used widely in science and engineering, this paper represents the first application for CFD equations. The computational domain is variable in spreadsheets and the practical engineering, i.e., aeronautical and mechanical, problems can be handled. Our SFD technique has the following features: 1) no prior knowledge of the computer language, 2) no program lines (e.g., Fortran coding), 3) built-in cells (grids), 4) visible computational domain during problem setup as well as computation, 5) interactive computation, and 6) computational results easily presented using the inherent graphics software.

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In-Flight Skin Friction Measurements Using Oil Film Interferometry

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Introduction

OIL film interferometry for quantitative skin friction measurement has been demonstrated successfully on an aircraft in-flight. Measurements were made during two flights of a Beech F33C Bonanza single-engine light aircraft at several locations on the wing upper surface and the flaps. Oil film interferometry is a direct skin friction measuring method first developed during the 1970s.[1–4] Transparent oil placed on a surface exposed to the airstream is thinned by the shear stress acting on it. In the original version of the technique, this thinning was measured by observation of the interference resulting from laser light reflecting from the air–oil interface and the oil–surface interface. The rate at which this thinning occurs can be related to the skin friction shear stress using lubrication theory.

The method makes use of readily available plastic sheets for optical surfaces and conventional illumination.[5–7] With several simplifying assumptions, only a single, postflight photograph of the interference pattern is required. The interference fringes can be viewed directly to obtain qualitative information or measured to obtain quantitative values of local skin friction. This technique has been demonstrated in low-speed, transonic, and supersonic wind tunnels,[5–8] but not on an aircraft in-flight.

A key assumption of this simplified method is that the skin friction coefficient ($C_{f\infty}$, defined as the local shear stress normalized by the freestream dynamic pressure) remains constant during the entire time the oil is exposed to the flow. Although this requirement is met easily in wind tunnels (perhaps only approximately in transonic and supersonic wind tunnels), the possibility of developing a flight profile with sufficiently brief takeoff and landing, off-condition, segments to satisfy this assumption remained unknown.

Procedure

Measurements were made during two flights. Adhesive-backed Mylar sheets (Monokote™, Top Flite Models, Inc., Champaign, IL) were placed on the surface to provide suitable optical properties to permit visible interference fringes. The locations are shown in Fig. 1. A line of transparent oil, in this case dimethylpolysiloxane (Dow-Corning, Midland, Michigan), was placed on the Mylar just before flight. For the first flight, oil with a nominal viscosity of 200 cS was used; for the second, higher-speed flight, a 500-cS formulation was used.

Lines of oil were applied just before flight. There were approximately 30 oil lines, most applied perpendicular to the freestream flow direction. Three oil lines also were placed at approximately 45 deg to the wing's leading edge. These lines, covering the upstream 30% chord of the wing at approximately midsemispan, were for the detection of boundary-layer transition. Because of the large

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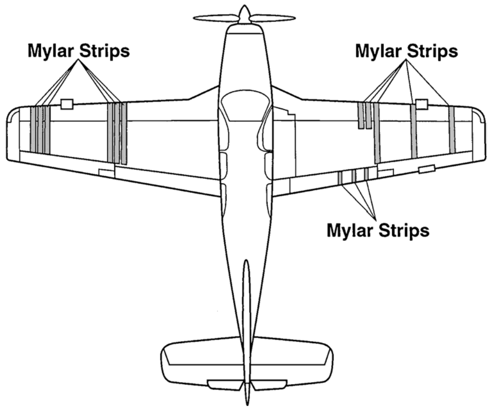

Fig. 1 Arrangement of Mylar strips on aircraft.

change in magnitude of the shear stress when the boundary layer becomes turbulent, a large change in fringe spacing was expected.

Postflight, the oil was illuminated by a light box fitted with mercury lamps, which have a strong green peak at 546.1 nm, and the resulting interference fringes photographed through a green filter on black-and-white film. The negatives then were digitized and the fringe spacing measured using a personal computer.

To obtain quantitative information, skin friction coefficients were calculated using a formula derived by Monson et al.[5] This required some oil properties, the wavelength of the illumination, and time histories of oil temperature and freestream dynamic pressure from the time the oil was applied until the interference was photographed. The oil temperature was taken to be the local surface temperature measured by a thermocouple installed on the left wing at approximately midchord, one-third of the distance from the fuselage to the wingtip. The freestream dynamic pressure was determined from the aircraft airspeed and altitude, which were continuously monitored and manually recorded. With this information, and the interference fringe spacing measured from the digitized photographs, the skin friction coefficient ($C_{f\infty}$) could be determined. Contributions to the uncertainty in these measurements comes from four sources: measurement of the fringe spacing, accuracy of the recorded flight conditions, validity of the constant-$C_{f\infty}$ assumption during takeoff and landing, and accuracy of the oil properties. The contributions from each of these sources were comparable in magnitude.

Results

The two flight profiles were designed so that the desired flight conditions were reached quickly, with minimal variation in angle of attack. The aircraft was stabilized on condition for approximately 30 min and then made a rapid descent and landing. Figure 2 shows the time history of freestream dynamic pressure and temperature for flight 1. It can be seen that the on-condition dynamic pressure was reached very quickly and held very nearly constant. Also evident is the variation in temperature associated with flight through areas of localized temperature variation as well as the temperature lapse with increasing altitude. This underscores the importance of monitoring temperature during flight testing, where temperature variations can be larger and less predictable than in wind tunnels.

During the first flight, the flaps were fully deployed with a test condition of 80 kn at 5000-ft pressure altitude. This required a full-flap takeoff. A route for the flight was chosen to minimize turns and the turns that were made were limited to coordinated turns with a maximum of 5-deg bank angle to maintain near-steady conditions. For the second flight, the flaps were fully retracted and an airspeed of 120 kn at 5000 ft was selected.

Interference fringe images were obtained following each of the two flights, including images of the diagonal oil lines clearly showing the transition location. Figure 3 shows an interference image of one of the diagonal oil lines from the first flight. The boundary layer is laminar with $C_{f\infty}$ decreasing—a smaller fringe spacing indicat-

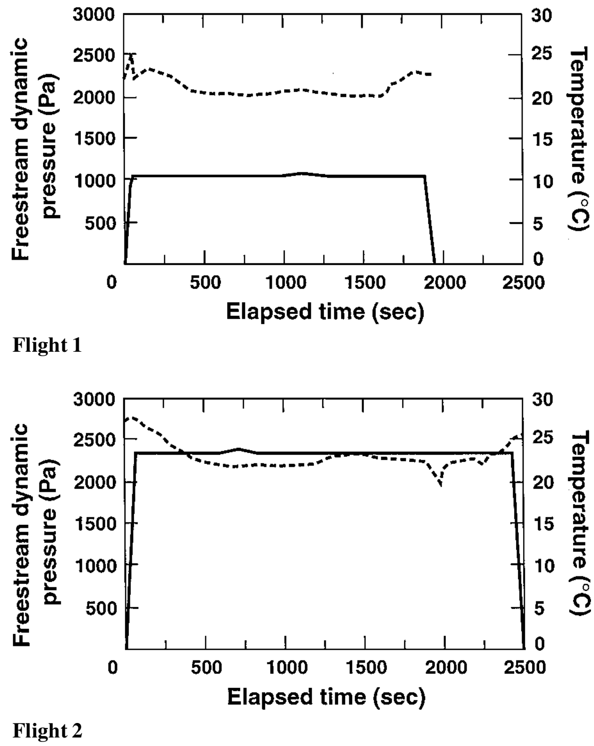

Fig. 2 Time history of freestream dynamic pressure and temperature for flight 1: - - - -, temperature, and ——, dynamic pressure.

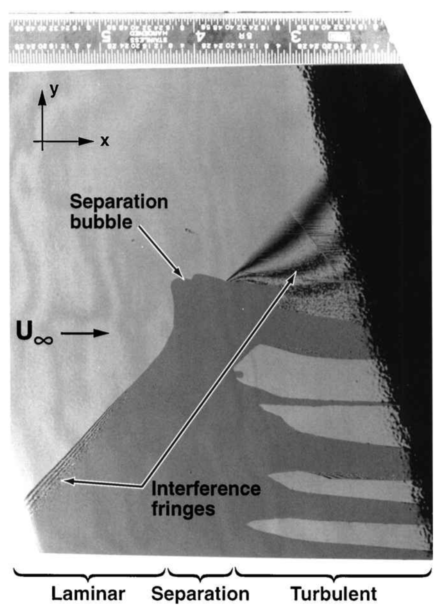

Fig. 3 Interference image showing boundary-layer transition and separation bubble from flight 1.

ing a smaller $C_{f\infty}$—until a point is reached where the oil has flowed forward, which was interpreted as indicative of laminar separation. Downstream of this, the boundary layer is turbulent. On the second flight, as seen in Fig. 4, transition occurs slightly farther aft, without any indication of separation.

Quantitative values for skin friction also were calculated from each oil line. Figure 5 shows the skin friction coefficient and uncertainty range from both flights. The results shown are taken from several slightly different span locations, collapsed to a single curve. For most data points, the uncertainties in the $C_{f\infty}$ values are estimated to be on the order of $\pm 10\%$, demonstrating the comparatively high degree of accuracy possible with this simple method of measurement.

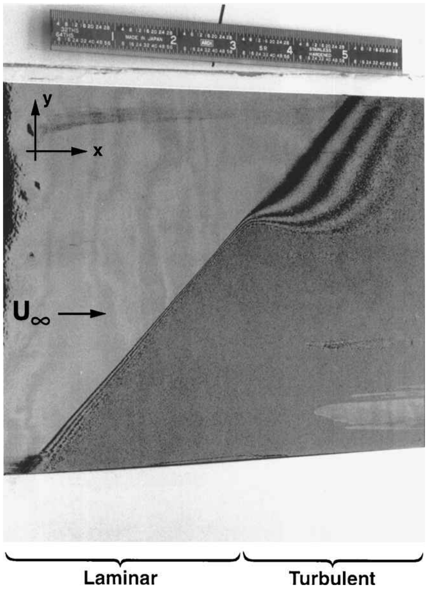

Fig. 4 Interference image showing boundary-layer transition from flight 2.

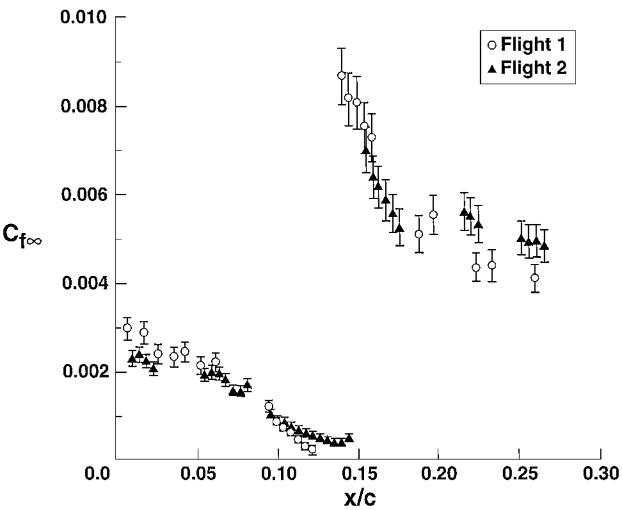

Fig. 5 Chordwise distribution of skin friction coefficient ($C_{f\infty}$ is the local shear stress normalized by the freestream dynamic pressure) at midsemispan for flights 1 and 2.

Conclusions

Oil film interferometry proved easier to use in a flight-test environment than anticipated, and interference fringe images sufficient to allow determination of skin friction within $\pm 10\%$ uncertainty were obtained for each flight at nearly all oil line locations. The location of boundary-layer transition was evident from abrupt change in fringe spacing.

Despite the relatively simple nature of the instrumentation and data recording used in this experiment, it was possible to obtain skin friction measurements at a large number of locations simultaneously. Using self-adhesive Mylar sheets to provide an optical surface made it possible to measure skin friction without modification of the aircraft. This method offers the possibility of making detailed skin friction measurements in flight testing more cheaply and easily than is possible with other methods.

Acknowledgments

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Dynamic Unstructured Method for Relative Motion of Multibody Configuration at Hypersonic Speeds

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Introduction

A WIDE variety of engineering problems include time-dependent flowfields resulting from the relative motion of multibody configurations. The fluid forces and the moments exerted on the involved boundaries, therefore, are unsteady, and they require time-accurate computations on dynamic meshes. Among the examples for such problems are rotor–stator interaction, rotorcraft dynamics, store separation, detachment of multistage-rocket components, separation of booster tanks from the space shuttle, piston motion in internal combustion engines, and heart valve and blood flow interaction.

Only recently, we have seen the emergence of methodologies to solve such problems. Examples by the prominent researchers of this topic may be found in Ref. 1. All of these solutions often require impractical amounts of computing time and resources. A discussion of the two competing approaches developed by the present authors can be found in Ref. 2. The present dynamic unstructured technique (DUT) method was initially developed[3,4] as an explicit time-integration method for flow speeds up to Mach 1.5. The present Note will report on the significant improvements that removed this restriction and increased its computational efficiency by an order of magnitude.

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