Application of Dual Hologram Interferometry to Wind-Tunnel Testing

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Introduction

THIS study shows that dual hologram interferometry can be used to accurately measure local densities in wind-tunnel experiments, and that this technique does not suffer from some of the serious limitations of previous interferometric methods. A pulsed ruby laser is used as the light source so that high-frequency turbulence in the flow can be instantaneously recorded, and hence, frozen in time.

The unique feature of dual hologram interferometry is that the no flow and flow conditions are recorded at different times on separate holograms. Because of this, movement between exposures is not recorded in the interferogram, and therefore, the method is not sensitive to wind-tunnel vibration. The images are interfered upon reconstruction, and the fringe configuration is controlled by precisely varying the orientation of the two holograms with respect to each other.[1-4] The heart of a practical, operational system is the dual hologram plate holder which is used to hold and precisely align the two holograms during image reconstruction. To demonstrate the accuracy and versatility of this method, three separate Mach 3 flowfields were considered in the original paper,[1] but only the flat plate turbulent boundary-layer results are presented here.

Optical System

The basic scheme is an off-axis, Toepler schlieren using a 7-in. collimated scene beam and a 2-in. collimated reference beam which is required to form the holograms and reconstruct the scenes.[1,3,4] Two light sources are used: a Q-switched ruby laser (25-mjoule energy output in a 20-nsec pulse) for hologram formation and a continuous wave helium-neon laser for system alignment and scene reconstruction. A big advantage of this system is that the real image is projected from the holograms during reconstruction. Hence, the flowfield phase and intensity information is stored for analysis after the test.

The dual hologram plate holder is a mechanical device which permits both holograms to be independently moved with 6° of precision control: 3 translational and 3 rotational. This device is the heart of the system and without it, the dual hologram method is impractical. With it, however, dual hologram interferometry is a practical, accurate and straightforward optical technique easy to apply to realistic tests.

Experimental Results

It has been demonstrated previously that the fringes produced by varying the relative orientation of the two holograms during reconstruction are valid and that the fringe shifts from the reference result from the recorded flow phenomena, not from adjustments in hologram orientation.[1,4] This capability permits the formation of an infinite fringe interferogram and finite fringe interferograms with any desired reference fringe spacing and orientation using the same pair of holograms. Additionally, shadowgraphs and schlieren photographs with various sensitivities can be produced from the flow hologram alone. No other optical technique can provide a variety of interferograms, shadowgraphs, and schlieren photographs of the same test at the same instant of time. These results have been reported previously and will not be presented here.[1-4]

The results for a compressible turbulent boundary layer on a flat plate are present here to show the accuracy and sensitivity of the dual hologram technique. Both finite and infinite fringe interferograms are used to analyze the turbulent boundary layer, and density profiles are determined from the fringe shift in the interferograms at a point 11 in. from the leading edge where the freestream Mach number and Reynolds number are 2.96 and 1.025×10^7, respectively. The static wall pressure, assumed constant through the boundary layer, is measured at this point and is used with the density data to calculate static temperature distributions. The total temperature is assumed constant and equal to the stagnation temperature measured in the calming chamber, and along the plate surface the static pressure gradient is assumed to be zero ($dp/dx = dp/dy = 0$); therefore, the velocity profiles can be calculated from the Crocco relationship.

The boundary-layer thickness is measured from the finite fringe interferogram because the edge of the boundary layer is better defined in this fringe configuration. The point where the ambient fringes bend sharply is the edge of the turbulent boundary layer. This measured thickness is used to nondimensionalize the vertical distances so that the velocity profiles can be compared to the $\frac{1}{7}$ power law and the finite-difference method[5] (Fig. 1). Previous experimental data for the same flow conditions obtained from pitot tube measurements have shown that the $\frac{1}{7}$ power law accurately describes the velocity profile through the turbulent boundary layer.

There is good agreement between the experimental data and the theory except close to the model wall. This is the region of the laminar sublayer in which the velocity and density gradients are sufficiently high for refraction to degrade the fringe contrast in the interferogram.

In order to determine the sublayer thickness, the data are compared to Clauser's law of the wall (Fig. 2). Since the law of the wall is valid for incompressible flow, the velocity data for the compressible flow are converted to incompressible values using Van Driest's compressibility transformation given in Hopkins et al.[6] The local skin-friction coefficient, calculated by iteration to fit the data to the law of the wall, is 0.00145. The

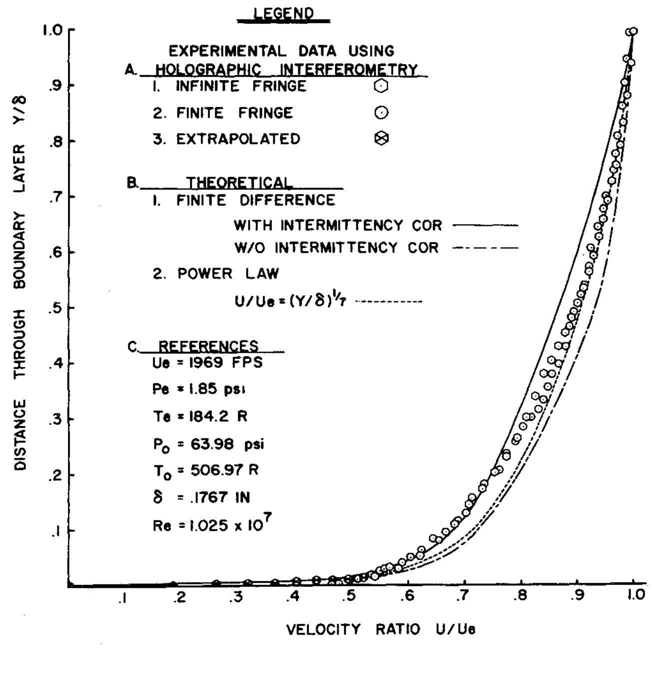

Fig. 1 Comparison between theoretical and dual hologram interferometric measurements in a supersonic turbulent boundary layer on a flat plate.

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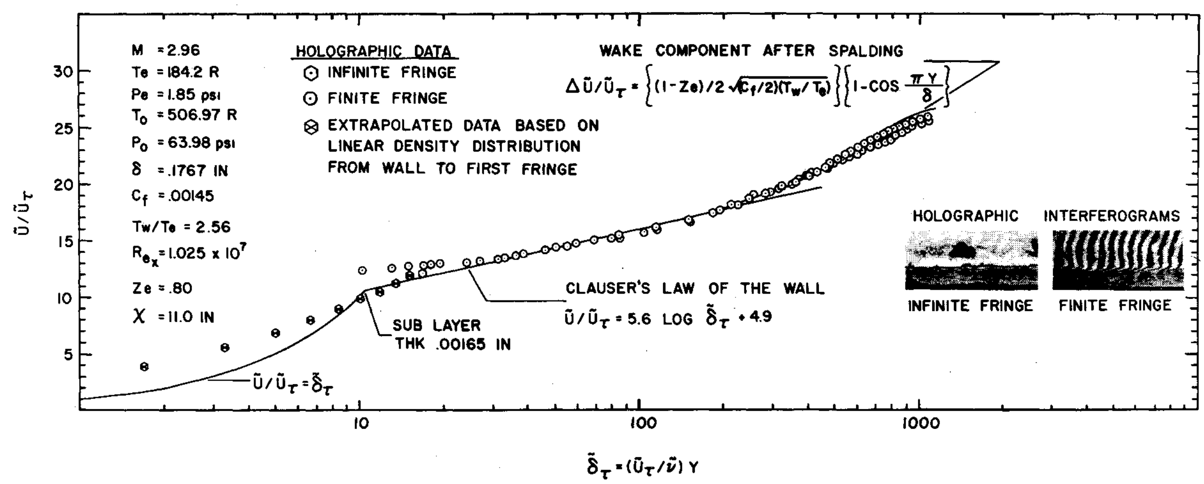

Fig. 2 Flat plate supersonic turbulent boundary-layer data transformed after Van Driest for comparison to Clauser's law of the wall.

Van Driest (II) theory predicts a $c_f = 0.00159$ for the specified Reynolds number, wall temperature, and Mach number of this test. This is well within the 10% rms deviation of other data from this theoretical c_f. For this test, the sublayer thickness is 0.0016 in.

The density distribution in the sublayer cannot be optically measured for two reasons. First, losses in fringe definition due to refraction are highest near the wall where the density gradient is the steepest. Second, the steep density gradient through the sublayer produces a high fringe shift over a very small distance, and this behavior cannot be seen in the interferogram. However, the density distribution can be approximated by assuming a linear change in density between the wall and the first measureable point nearest the wall, and the velocity can be calculated as before. The velocity distribution calculated from the extrapolated density data is plotted in both Figs. 1 and 2, and these results indicate that a linear density distribution through the sublayer is a reasonable assumption.

Conclusions

The turbulent boundary-layer results, in addition to previous results, show not only that control of the optical reference is possible and valid, but also that it provides an optical measuring sensitivity not available with other systems or techniques. The technique employs an optical system which is simple except for the dual hologram plate holder which is needed to precisely reposition the holograms during image reconstruction. Control of the optical reference also makes possible the elimination of stray fringe shifts due to component movement between exposures, which has been a serious problem in wind-tunnel testing where tunnel vibration is a significant problem to optical measurements.

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Transverse Shear in Laminated Plate Theories

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THE use of composite materials in the design of thin-walled structures has caused a recent interest in laminated plate theories. Two of the most inclusive theories are given by Whitney and Pagano,[1] and Yang, Norris, and Stavsky.[2] Both of these theories follow the basic approach set forth by Mindlin[3] for homogeneous plates, and include transverse shear and rotary inertia considerations. In this Note a new method of extending Mindlin's theory for the treatment of transverse shear effects to laminated plates will be presented.

The main difference between the approach of Refs. 1 and 2 and the present approach is that, in the former an approximate displacement field is used to evaluate the strains in each layer. The resulting interlaminar shear strain is constant across the thickness, and the shear stress is discontinuous at the layer interfaces, which violates the continuity of stress. In the present approach, the shear stress is assumed continuous and constant across the thickness and the shear strain is allowed to be discontinuous. An average shear strain is then introduced and related to the plate displacements. It will be shown that the present approach satisfies all the interface boundary conditions; it also yields a discontinuous transverse shear strain and a piecewise smooth in-plane displacement which better approximates the exact solution.

The solution of a boundary value problem is also considered.

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