Quantitative Determination of Three-Dimensional Density Field by Holographic Interferometry

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Theme

THE principal objective of this paper is to report a successful application of holographic interferometry to a large-scale wind-tunnel experiment. Emphasis is placed on the quantitative determination of the three-dimensional density field under investigation. A rational procedure is developed which makes the proper use of an efficient data-reduction theory to calculate three-dimensional density fields around opaque bodies. This new procedure eliminates the major difficulty in three-dimensional data-reduction involving opaque objects, and is used to reduce the three-dimensional density data from the interferograms produced in the experiment. Good agreement between experiment and theory is achieved.

Contents

The holographic system was conveniently set up in a conventional schlieren bench of Supersonic Tunnel No. 1 at the Naval Surface Weapons Center. The large end mirrors (40-cm diam) were particularly suitable for a large area coverage of the flowfield. The holographic arrangement is schematically shown in Fig. 1. Note that interferograms for quantitative use were all produced by using collimated light for both the object beam and the reference beam. The light source was a pulsed-ruby laser ($\lambda = 6943\,A$), and optical alignment was made with a cw He-Ne laser. Many details of the work also appear in Ref. 1, in addition to the full paper

The specific experiment conducted was the supersonic flow over a 15° half-angle cone at a nominal Mach number of two. The cone was about 30-cm long and made of aluminum. Both the axisymmetric case and the asymmetric case with the cone at yaw were studied. The wind tunnel has a 40-cm x 40-cm open-jet test section, and the model was sting supported. In the asymmetric runs, the 90° angular coverage required for data reduction was achieved by rotating the cone model in a 6° interval about the wind-tunnel axis with the sting support holding the model at a fixed (intended) angle of attack of 15°. It was carefully determined later that the deflection of the model by the lift force changed the angle of attack from its intended value to an effective value of 16.5. The viewing angle ϕ varied from $0-90°$ as the angle of attack α moved from the yaw plane to the pitch plane.

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The conventional double-exposure technique was employed to take holographic interferograms of the flow. A photo print of a typical interferogram of the asymmetric flow is shown in Fig. 2.

Since the object beam had a fixed orientation perpendicular to the vertical *(x-y)* plane, fringe-shift data *g* were measured along the vertical line in each interferogram. Figures 3 and 4 show the fringe shift per unit cone length g/ℓ as a function of R/r_c, the vertical distance from the cone axis normalized by the local cone radius, for the axisymmetric case and some typical asymmetric cases, respectively. Because of the largely inviscid (conical) nature of the flow, g/ℓ is independent of ℓ. This property allowed the readings to be taken at any convenient axial station for each interferogram. Readings were generally taken at stations about 2/3 of the cone length from the tip. The dotted portion represents the region of missing fringes caused by model blockage.

The directly reduced density data were in a plane perpendicular to the freestream [with polar coordinates (R, ϕ'')] ϵ To compare the experimental data with theoretical data[2] given in a plane perpendicular to the cone axis [with polar coordinates (r, ϕ')], the density field of Ref. 2 was mapped onto the plane perpendicular to the freestream.

In the data reduction, we follow the theory developed in Refs. 3 and 4. It is derived in the refractionless limit, using

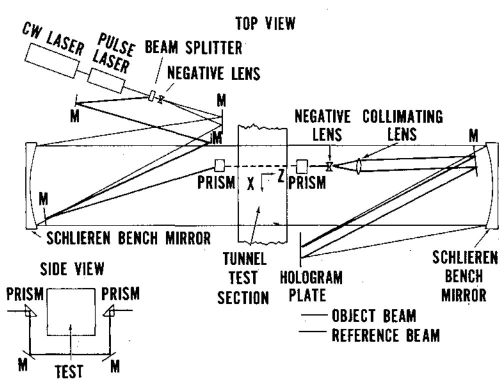

Fig. 1 Schematic of holographic interferometer.

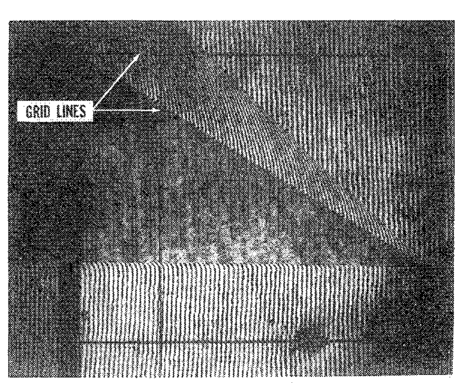

Fig. 2 Holographic interferogram: asymmetric flow $\phi = 90°$.

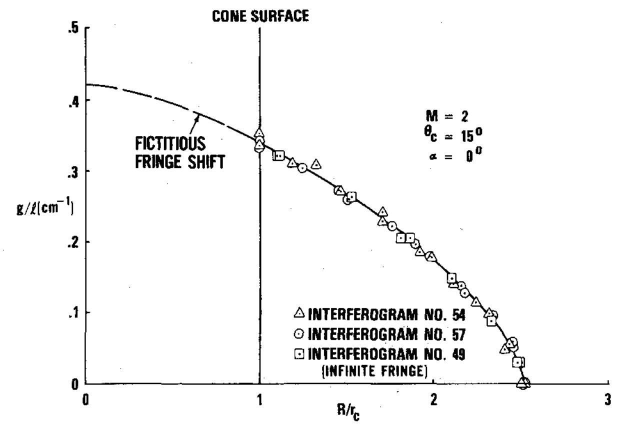

Fig. 3 Experimental fringe shift: axisymmetric flow.

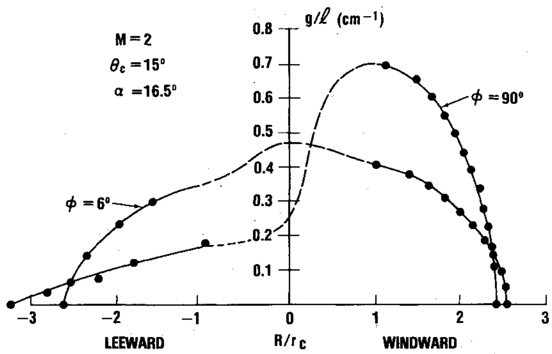

Fig. 4 Experimental fringe shift: asymmetric flow.

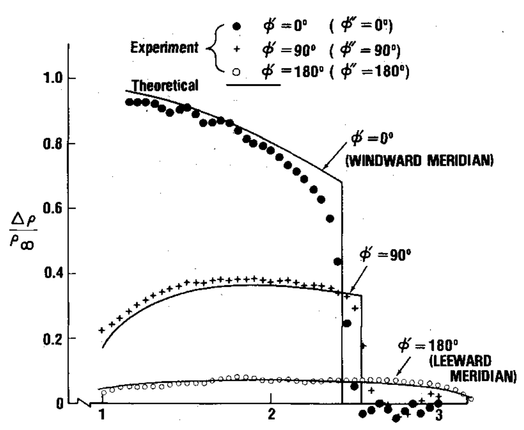

Fig. 5 Density results: asymmetric flow.

two-dimensional Fourier transform technique. This theory has been numerically programed by Van Houten.[5] It requires, among other things, that $g(R, \phi)$ be provided continuously over the entire interferogram for each viewing direction. A direct application of the theory to the present experiment was thus not possible because of the missing fringes in each view (see Figs. 3 and 4). Numerical experiments[1,6] showed that the empirical approach of completing the g-curves by independent interpolations for each view, as was done in Ref. 7, would generally lead to erroneous results, except for the case of axisymmetric flow. The difficulty is common to all existing three-dimensional data-reduction theories of analytical nature.

In the present work, a rational procedure is developed to resolve this difficulty. It is based on an invariant property of the area under the g-curve. A general account of the procedure can be found in Zien.[6] Only the basic idea will be briefly explained here. In the refractionless limit, the area under the g-curve must be invariant with respect to the viewing direction if the region of data reduction corresponds to a uniquely defined density field. Therefore, a necessary condition for properly using the data-reduction theory is to complete the g-curves for various views in such a way that all the areas under the g-curves are equal. For example, the areas under the two curves in Fig. 4 must be made equal by properly choosing g_f's (i.e., the dotted curves). For the axisymmetric case where only one view is needed in the data reduction, this condition is automatically satisfied by an arbitary choice of g_f. Observing the area-invariant property may not be sufficient to define a unique, fictitious density field to replace the opaque object. More constraints may have to be imposed in order to determine the area distribution under g_f. However, in most aerodynamic applications, the necessary condition alone appears to be adequate. In practice, the approximate equality of area was achieved in a trial-and-error manner.

Final results of experimental density distribution are presented in Fig. 5 for the asymmetric case, where the corresponding inviscid calculations[2] are also included for comparison. A similar comparison for the simpler case of axisymmetric flow is given in the full paper; the agreement in $\Delta\rho/\rho_\infty$ is better than 6%. In view of the expected small viscous effects (also evidenced by the interferogram) the good agreement between theory and experiment reflects the accuracy of the experimental results and the success of the quantitative application of holographic interferometry to large-scale wind-tunnel experiments.

References

[1] Zien, T.F., Ragsdale, W.C., and Spring, W.C., "Quantitative Applications of Holographic Interferometry to Wind-Tunnel Testing," NOLTR 74-96, Dec. 1974, Naval Surface Weapons Center, White Oak Lab., Silver Spring, Md.

[2] Jones, D.J., "Tables of Inviscid Supersonic Flow About Circular Cones at Incidence, Parts I and II," AGARDograph 137, Nov. 1969.

[3] Rowley, P.D., "Quantitative Interpretation of Three-Dimensional Weakly Refractive Phase Objects Using Holographic Interferometry," *Journal of Optical Society of America,* Vol. 59, Nov. 1969, pp. 1496-1498.

[4] Junginger, H.G. and Van Haeringen, W., "Calculations of Three-Dimensional Refractive-Index Field Using Phase Integrals," *Optics Communications,* Vol. 5, April 1972, pp. 1-4.

[5] Van Houten, P.E., "The Application of Holographic Interferometry to the Determination of Discontinuous Three-Dimensional Density Fields," A.E. thesis, Naval Postgraduate School, Monterey, Calif.,Dec. 1972.

[6] Zien, T.-F., "Data Reduction from Interferograms of Three-Dimensional Flows Around an Opaque Model," July 1974, *International Workshop on Three-Dimensional Image Reconstruction Techniques,* Brookhaven National Lab., Upton, N.Y., to be published.

[7] Jagota, R.C. and Collins, D.J., "Finite Fringe Holographic Interferometry Applied to a Right Circular Cone at Angle of Attack," *Journal of Applied Mechanics,* Vol. 39, Dec. 1972, pp. 897-903.