This tangential drag coefficient on the prototype will depend on cable roughness whereas the model Reynolds number may be low enough that the coefficient is independent of roughness. Thus, similarity on tangential drag will depend on prototype roughness and may not be satisfied. For forced oscillations of bare cables the largest displacements will be normal to the cable and lack of similarity in the tangential force will not change significantly the cable tension or amplitude of motion.

In Eq. (19) the velocity U is shown to scale as $\lambda^{1/2}$. In the case of a buoy heaving and surging in a seaway or a heaving or pitching ship towing a depressor the velocity is proportional to an amplitude times a frequency, $U = Pf$. Since frequency is angle per unit time, f scale as $\lambda^{-1/2}$. Thus, the amplitude of the input P scales as λ.

$$P_m/P_p = \lambda, f_m/f_p = \lambda^{-1/2} \tag{26}$$

A Strouhal number based on the amplitude of the cable motion at a boundary is thus satisfied on model and prototype. These equations complete the scaling laws required to test models of cable.

References

[1] Hansen, A. G., *Similarity Analyses of Boundary Value Problems in Engineering*, Prentice-Hall, Englewood Cliffs, N.J., 1964.

[2] Wilson, B. W., "Characteristics of Anchor Cables in Uniform Ocean Currents," TR 204-1, 1960, Texas A and M Research Foundation, College Station, Texas.

[3] Casarella, M. J. and Parsons, M., "Cable Systems Under Hydrodynamic Loading," *Marine Technology Society Journal*, Vol. 4, No. 4, July–Aug. 1970, pp. 27–44.

Holographic Interferometry of a Submarine Wake in Stratified Flow

Arvel B. Witte*
TRW Systems Group, Redondo Beach, Calif.

A NEW technique, holographic interferometry, has been used to visualize a submarine wake in stratified flow. Shadow and schlieren techniques have been used by other investigators to study stratified flows, but examples of interferometry have not been reported. Pao[1] used the shadow technique to study qualitatively the structure of turbulence in the wake of a cylinder towed through a stably stratified salt water solution. Mowbray[2] used the schlieren technique to study internal waves in a density stratified fluid. The inherent advantages of using interferometry rather than schlieren or shadow techniques to extract quantitative data about flows, have been discussed elsewhere.[3] The specific advantages afforded by using holography, for example, 1) the use of nonprecision optics, 2) depth focusing, and 3) three-dimensional viewing of the flowfield, may make this technique valuable in recording and reducing three-dimensional holographic interferograms to three-dimensional density field. The purpose of this note is to describe the experimental technique and show and discuss some of the experimental results.

A self-propelled model submarine, about 1 in. in diameter and $4\frac{1}{2}$ in. long, was operated in a plexiglas tank 4 ft long and 1 ft square. The submarine was guided by a pair of 0.010-in. wires and powered by a d.c. power supply. A hologram of the submarine in pure water is shown in Fig. 1. A 1-in.-mesh grid, slightly tilted with respect to the plane of the picture, is shown along with the guide wires and power leads. In the experiments which followed the submarine was positioned 2 in. below the water surface and 6 in. above the bottom of the tank. The top 2 in. were pure water; the bottom 6 in. were salt water (NaCl) having a salt mass fraction of 0.01.

The pulsed ruby laser holograph used to record the holographic interferogram has been used in the study of high-speed projectile wakes and is described elsewhere.[4] Because the holographic process records both amplitude and phase a common path interferometer is used in which double exposure of the comparison scene hologram and the test scene hologram is made sequentially in time on one photographic plate. The superposition of these two holograms forms the interferogram. Modification to the holocamera to record the stratified flow pictures was minor. An additional tank of water having the same optical path length as the one in the test section containing the submarine, was placed in the reference beam of the laser to maintain longitudinal coherence of the holocamera.

A finite fringe holographic interferogram of the submarine wake recorded at 4 body lengths behind the submarine moving at 4 fps is shown in Fig. 2. The vertical wires shown in the lower third of the picture are evenly spaced across the width of the tank and serve as objects to focus on when utilizing the depth focusing property of holography. Changes in index of refraction were caused by fluid displacements attending the submarine passage and turbulent wake mixing processes. The nominally vertical parallel fringes observed in the lower portion of the picture denote the undisturbed background fringe pattern. The shifted, irregularly shaped fringes observed in the upper two-thirds of the picture are caused by the changes in the aforementioned refractive index. The fringe shift from the undisturbed position measures the integrated change in refractive index along the light path. Shifts to the left or right denote an increase or decrease in average optical path, respectively.

Two observations which are immediately apparent are that 1) the wake forms an irregular fringe pattern of fringe shift equal to about 1 to 3 fringes (this pattern runs across the central part of the picture), and 2) water cooling at the air-water interface caused a large fringe shift denoting an increase in optical path there.

The fringe shift in the wake is order one. Had a cylinder of uniformly mixed pure and salt water resulted from the passage of the submarine, the fringe shift would have been about 25 fringes. Thus, at 18 submarine diameters it appears

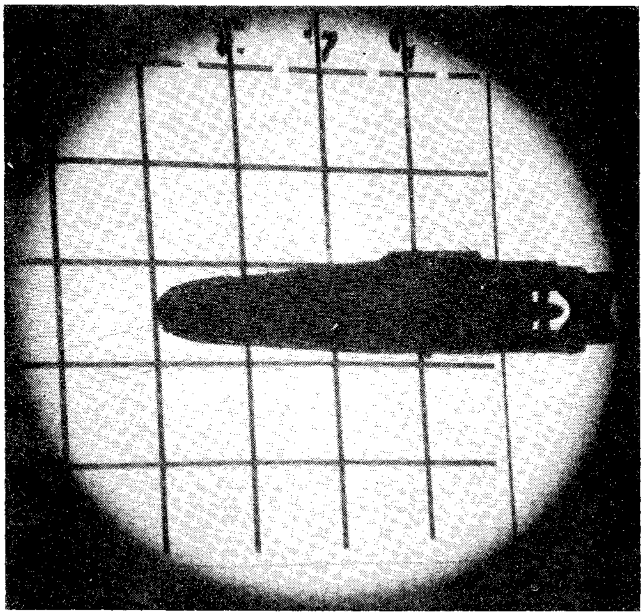

Fig. 1 Hologram of submarine in pure water.

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* Head Experimental Staff, Fluid Mechanics Laboratory.

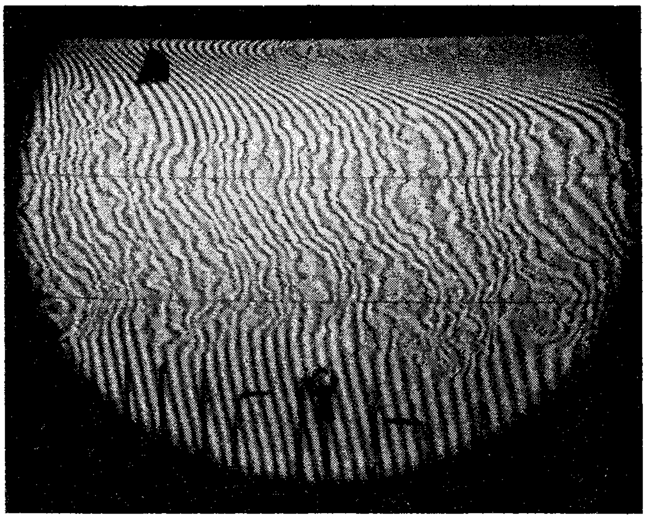

Fig. 2 Holographic interferogram of submarine wake in stratified flow.

that the two miscible fluids—pure water above and salt water below the submarine—are not well mixed. This observation may well be caused by a return of the fluid mixed by the propeller to the initial density stratification. If the mean density profiles are axisymmetric, the data could be reduced by a modification of the Abel inversion integral. Data reduction of this type has not been attempted. Localized turbulent statistics can be measured by cross viewing the data from a single hologram. This concept has been applied to the data reduction of the projectile wakes elsewhere.[5]

The tank was filled about 30 min prior to running the experiment. This time is probably enough time to set up thermal equilibrium of the air-water and wall-water interfaces surrounding the fluid. However, 10 min before recording the data, the tank, which was mounted on rails, was rolled into the test section of the holocamera. This movement probably disturbed the thermal layers surrounding the fluid. Since the interferogram is recorded as a time sequence of two holograms, it is suspected that the large fringe shift (5 fringes) within the first centimeter of the surface is caused by surface layer cooling by evaporation during the time interval, which was about 1 min. Reduction of the fringe data at the interface shows that this fringe shift corresponds to temperature drop of a maximum of 0.1°C. Because thermal layers in equilibrium are known to have a temperature difference of several tenths of degrees, this surface layer phenomena could be explained this way.[6,7] The irregularities in fringe pattern at the interface may be caused by submarine disturbances or by convective recirculation or both.

References

[1] Pao, Y.-H., "Turbulence Measurements in Stably Stratified Fluids," Feb. 1970, Flight Sciences Lab., Boeing Scientific Research Lab., Seattle, Wash.

[2] Mowbray, D. and Rarity, B., "A Theoretical and Experimental Investigation of Phase Configuration of Internal Waves of Small Amplitude in a Density Stratified Liquid," *Journal of Fluid Mechanics*, Vol. 16, April 1967, pp. 1–16.

[3] Ladenburg, R. W. and Bershader, D., "Interferometry," *Physical Measurements in Gas Dynamics and Combustion*, Pt. I, Art. A-3, 1954, pp. 47–78.

[4] Witte, A. B. and Wuerker, R. F., "Laser Holographic Interferometry Study of High Speed Flowfields," *AIAA Journal*, Vol. 8, No. 3, March 1970, pp. 581–583.

[5] Witte, A. B., Fox, J., and Rungaldier, H., "Holographic Interferometry Measurements of Mean and Localized Fluctuating Wake Density Field for Cones Fired at Mach 6 in a Ballistic Range," AIAA Paper 71-564, Palo Alto, Calif., 1971.

[6] Adams, J. A. and Meier, L. B., "Density Gradients Near a Liquid/Air Interface," Rept. 6828, March 31, 1969, Naval Research Lab., Washington, D. C.

[7] Adams, J. A. and Meier, L. B., "The Effect of a Submerged Heater on the Heat Transfer Near an Evaporating Surface," *Chemical Engineering Symposium Series*, Vol. 66, No. 102, 1970.

Pollution Monitoring: An Engineering Challenge

J. M. Snodgrass*

Scripps Institution of Oceanography, La Jolla, Calif.

WITHOUT question, pollution has emerged as one of the key "buzz words" of the early 1970's. Pollution has long occupied the realm of the biologists and is no stranger to the political arena. By now it has become quite clear that, if we are to make headway against undesirable pollution, we must begin with facts and facts in turn are validated by measurement and numbers.

We have made an exceedingly abrupt beginning and have come already face to face with our problem which is, how do we go about making the necessary measurements and obtaining essential numbers? It is not our purpose to debate the question of whether we need monitoring systems for pollution measurements or not but rather to address specifically the question of how we may go about the measurements of marine pollution. Today most pollution measurements are made by utilizing manned "monitoring" stations. By implication, manned stations implies that man hours are required. In fact, very large numbers of man hours may be required for collecting samples and carrying out the subsequent analytical analysis. With present techniques, the labor costs tend to be the dominant parameters for large-scale monitoring systems.

From the engineering standpoint, there is a very great challenge in that sensors for monitoring pollutants for the most part simply do not exist and there is no such thing as "off-the-shelf" availability. At the very least, major development of sensors is badly needed and in most cases the sensors have not yet been invented.

Perhaps it is well to elaborate at this point as to the implication of the term sensor. It is quite true that measurements are now being made of pollutants in the marine environment but this is often done by collecting extensive samples and carrying out a variety of chemical manipulations in which the actual measurements may be made by means of various chromatographic techniques. The chromatograph as the end element in the analytical technique employed may be considered to be a sensor, but this is not the kind of sensor which we are considering. We are considering a sensor to be a relatively simple package device that is capable of responding to the desired measurand and supplying as an output an electrical signal proportional to the concentration or magnitude of the measurand. A temperature sensor such as a thermocouple or a thermistor would be considered to be ideal simple sensors and a pressure sensor such as a vibrotron would also satisfy our requirement. Further, a suitable sensor should be capable of operating in an unmanned, unattended system for protracted periods of time. Specifically, we are concerned with the feasibility of developing sensors in lieu of complicated analytical techniques.

Our purpose in presenting this material is to bring to the

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* Research Engineer, Special Developments Group, Scientific Support Division.