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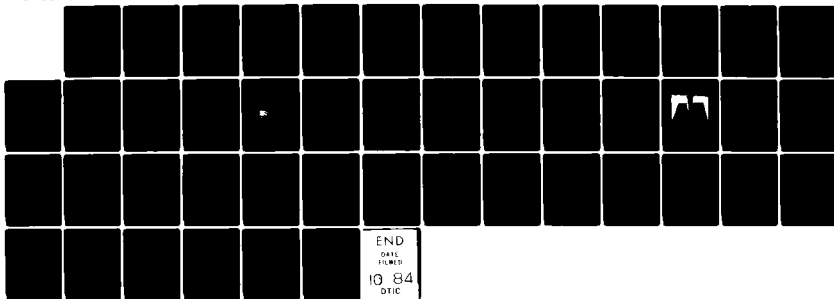
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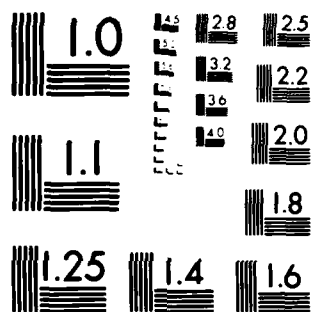
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**DAVID W. TAYLOR NAVAL SHIP
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Bethesda, Maryland 20084

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**NEW APPROACHES TO HYDRODYNAMIC FLOW VISUALIZATION
ON SURFACES**

P.K. Besch
and
M.S. Alvarado

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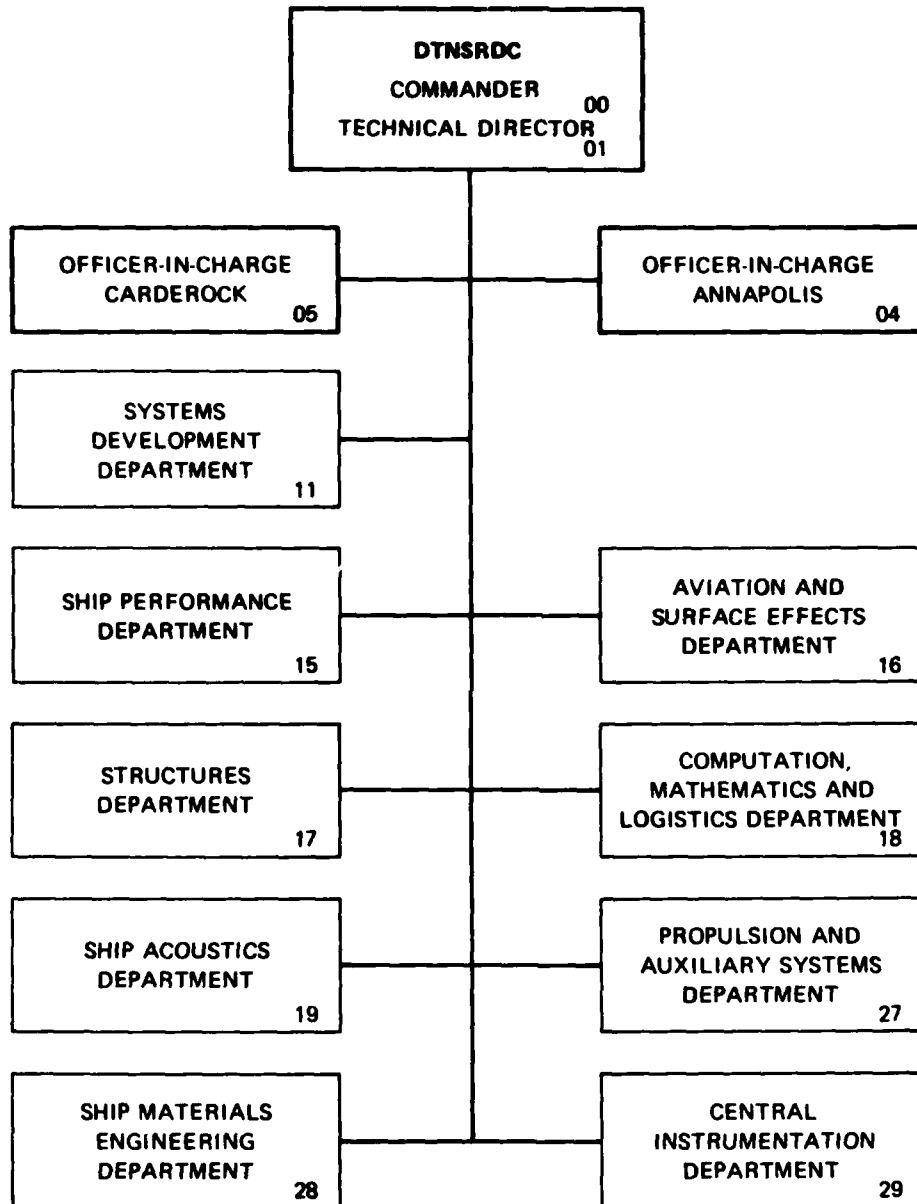
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NEW APPROACHES TO HYDRODYNAMIC FLOW VISUALIZATION ON SURFACES

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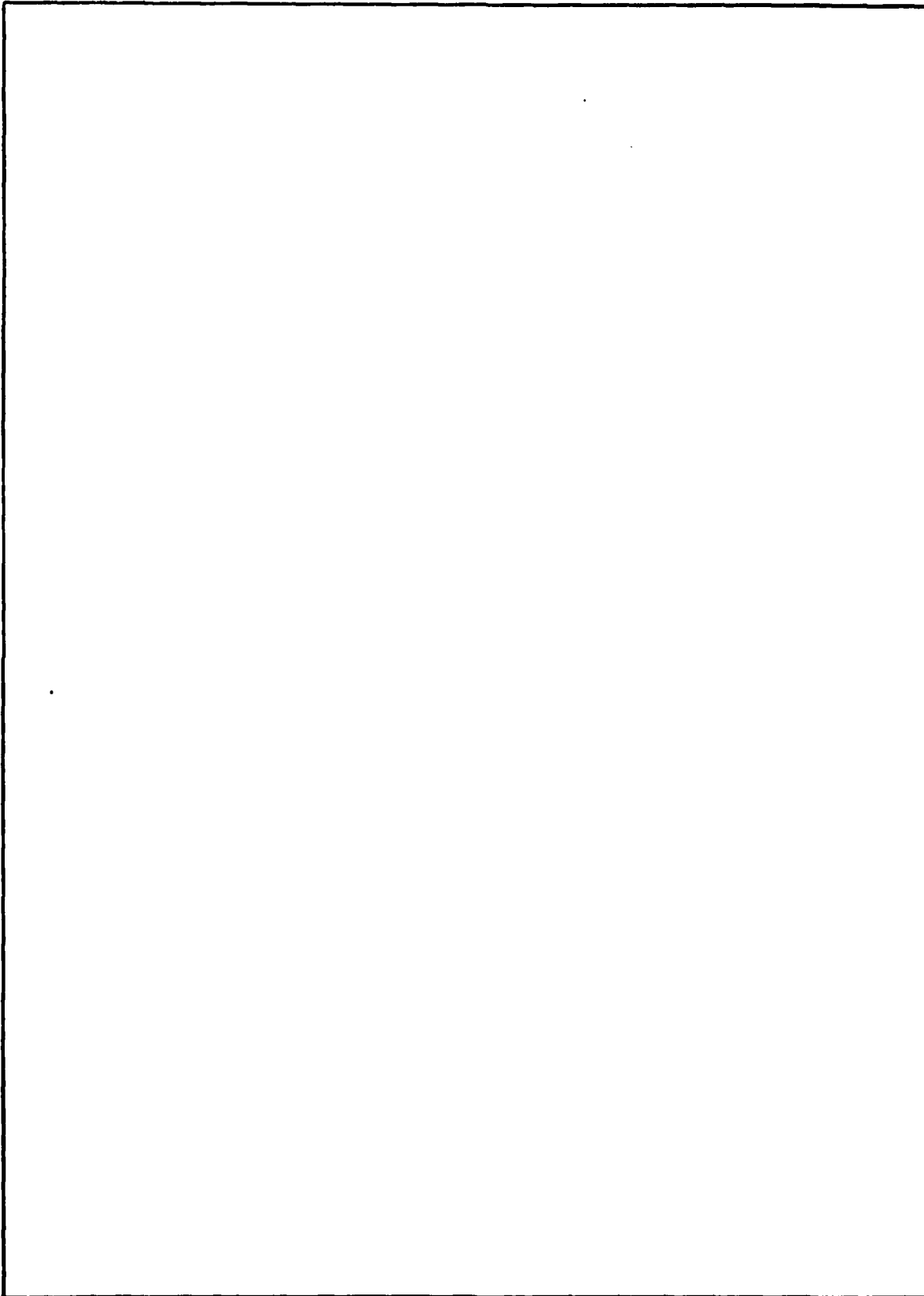
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ABSTRACT

A wide range of technologies was surveyed to find promising new techniques of visualizing hydrodynamic flow phenomena on surfaces. Various forms of coating were considered: liquids, erodable solids, small tufts, chemicals, liquid crystals, and optically deformable coatings. Experimental and conceptual studies indicate that high-viscosity fluids for dot patterns, optical techniques with soft coatings, and liquid crystals in modified form, may provide improved flow visualization. However, each of these techniques requires further development as specified in the report.

ADMINISTRATIVE INFORMATION

This work was supported by the General Hydrodynamics Research program, administered by the David Taylor Naval Ship R&D Center, under Work Unit 1-1543-102.

INTRODUCTION

Hydrodynamic research and development experimentation in most cases is concerned with the interaction of a solid body and an impinging water flow. Many of the questions to be answered critically depend upon the nature of the boundary layer flow on that body. Good flow visualization (FV) techniques can both reveal the flow features on bodies and ensure that other measurements are not made blindly. This information is particularly important when small-scale models are being employed.

Although FV techniques are being used more widely in research work as time goes on, virtually no hydrodynamic research routinely utilizes a surface FV coating when no specific objective calls for it. Available techniques, though of some effectiveness, have many deficiencies which reduce their usefulness. These deficiencies variously include facility contamination, premature activation, inadequate resolution, long recycling time, and difficulty of installation.

It is noted that there has been very little new development in surface FV techniques in water over the past several years. Even the considerable research activity in turbulent boundary layer flow has employed only dye injection or tracer particles rather than some form of material attached to the surface.

These approaches reflect the interest in microscopic flow structure rather than in identifying macroscopic flow features. Monitoring such macroscopic features is a qualitative task which can yield considerable insight into the nature and prediction of forces acting on a body.

The present work has endeavored to overcome many of the deficiencies of existing surface FV techniques by identifying other technological approaches which avoid those deficiencies. The ultimate objective is a number of techniques which can be employed routinely in both scale-model towing experiments and in research projects combined with other flow field and force measurements.

Initially, the objectives of current hydrodynamic research and development experiments were analyzed to determine the needed boundary layer characteristics. Secondly, a list of requirements was drawn up to meet those objectives while being feasible and practical. Third, a wide range of technologies was surveyed to determine candidate approaches. Approximately thirteen of these candidate approaches were analyzed either in simple experiments or conceptually. Results for most approaches are described in this report; others were completely ineffective.

Although most concepts proved unworkable, at least in the short time that was available for testing, three general categories of approach were viewed as having potential value: high-viscosity fluids for dot patterns, optical/compliant coating methods, and liquid crystal coatings. However, these new approaches all require further development before precise guidelines for everyday use are available.

CURRENT EXPERIMENTAL RESEARCH OBJECTIVES

EXPLICIT OBJECTIVES

To a large extent, the objectives of flow experiments conducted in naval and related facilities are to achieve smooth, unseparated (for low drag), non-cavitating flow over (usually) closed bodies, including attached appendages. Additionally, it is desired that transition from laminar to turbulent boundary layer flow occur at a known location, usually near the transition location of a full-scale prototype of the model being tested. In addition to direct observations of these characteristics on scale models, validations of theoretical analyses are often required.

The following examples of the above objectives are provided for illustration: On large models of surface ship hulls, alignment of bilge keels, various support struts, rudders, and anti-roll fins is performed using flow direction on and near the hull. On propeller blades, regions of separation, extent of laminar vs. turbulent flow, and directions of skin friction (indicating differences between potential flow and actual flow), are needed. Research into relationships between boundary layer flow and cavitation inception is conducted using headforms having transition and separation zones indicated. The effectiveness of artificial transition stimulation devices, and the location of natural transition, may be observed on many types of models. The behavior of vortices in proximity to model surfaces is also studied with FV techniques.

IMPLICIT OBJECTIVES

The explicit objectives described above may be reduced to determining a number of characteristics of the boundary layer, and/or the pressure distribution on model surfaces. These characteristics are:

<u>Characteristic</u>	<u>Application</u>
Skin friction direction	Alignment of keels, struts, control surfaces; validation of propeller design predictions; detection of separation; vortex behavior
Skin friction magnitude	Detection of transition and separation; vortex behavior
Pressure magnitude (steady and unsteady)	Detection of cavitation inception and separation; validation of pressure distribution predictions

Determination of these surface flow characteristics is complicated by the wide range of speed, ambient pressure, model shape and size, facility access, and type of motion within which typical models are operated. Thus, techniques which can be adapted to a wide range of conditions must be given priority. An indication of the range of skin friction magnitude and pressure magnitude experienced by a 20-ft (6.1m) long submarine model at typical model speeds is

given in Figure 1. Analogous plots for a propeller blade would show values between one and two orders of magnitude larger. A further variable influencing some observations (transition-related pressure spiking, propellers in nonuniform wakes, vortex shedding) is unsteadiness of the pressure and skin friction.

It is noted that to some extent the operating conditions of a model may be altered to accommodate requirements of FV. Variations usually involve lower speed (skin friction magnitude) to permit dye injection under laminar conditions. It would be acceptable in some cases to operate a model at lower or higher speed or at a different static pressure to match the sensitivity range of a particular technique.

REQUIREMENTS FOR ACCEPTABLE TECHNIQUES

The above objectives have been rephrased into a list of design-type requirements which are given below.

PERFORMANCE REQUIREMENTS OF FV TECHNIQUES

1. Information is required on one or more aspects of surface flow which is/are related to performance of hydrodynamic models. These aspects include:

- (a) skin friction direction
- (b) skin friction magnitude
- (d) pressure magnitude (steady or unsteady as in turbulent flow);

The information may be either quantitative or qualitative, and must apply to the run condition of interest rather than reflecting flow startup or shutdown.

2. Information is required at a large number of closely spaced points, or in a continuous distribution, rather than at a small number of points.

3. The technique cannot significantly interfere with (alter) the natural flow around model.

4. The technique must be either semi-permanent (remains on model after removal

Figure 1 - Hydrodynamic Pressure and Shear Stress Calculated to Occur on the Surface of a Submarine Model

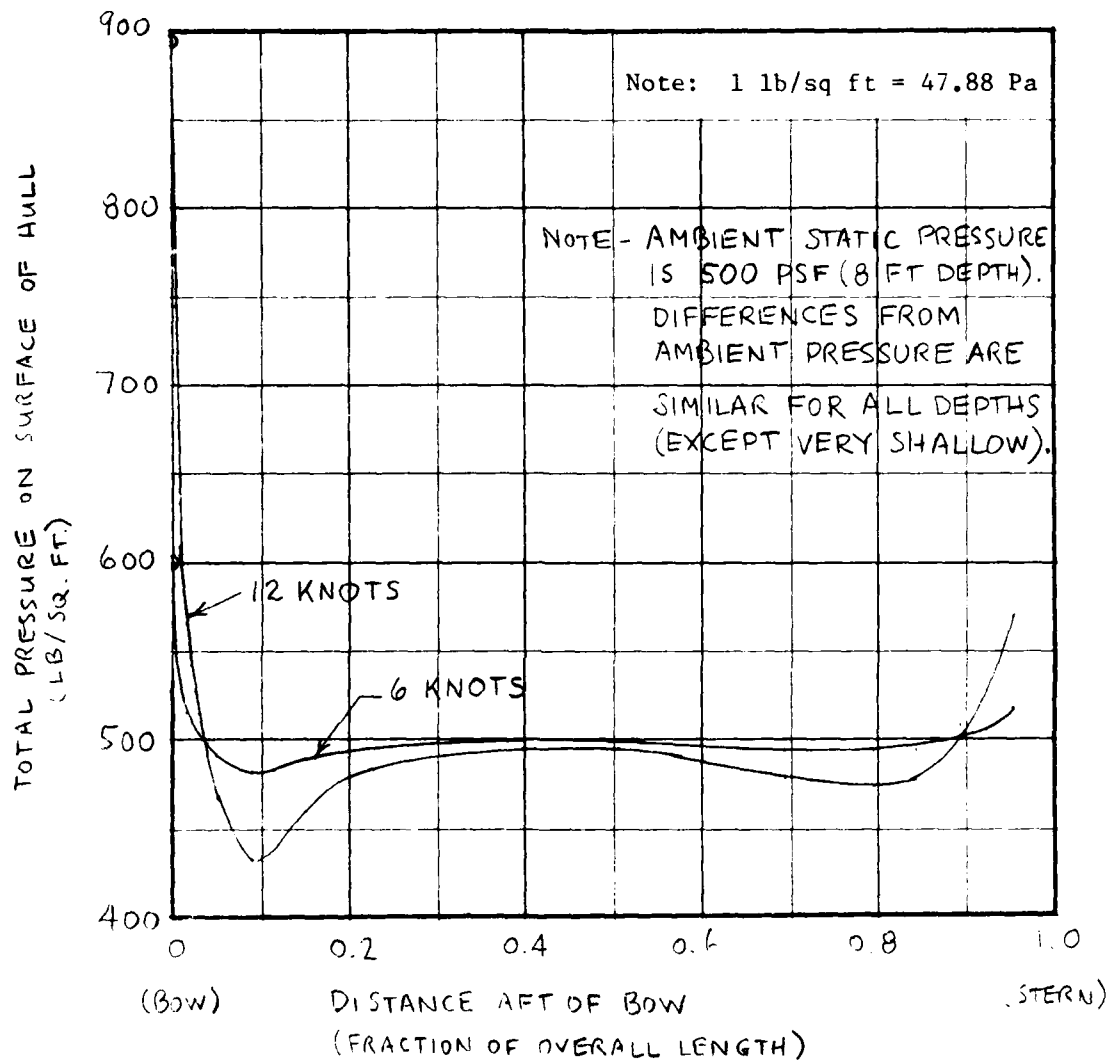


Figure 1a - Surface Pressure Distribution

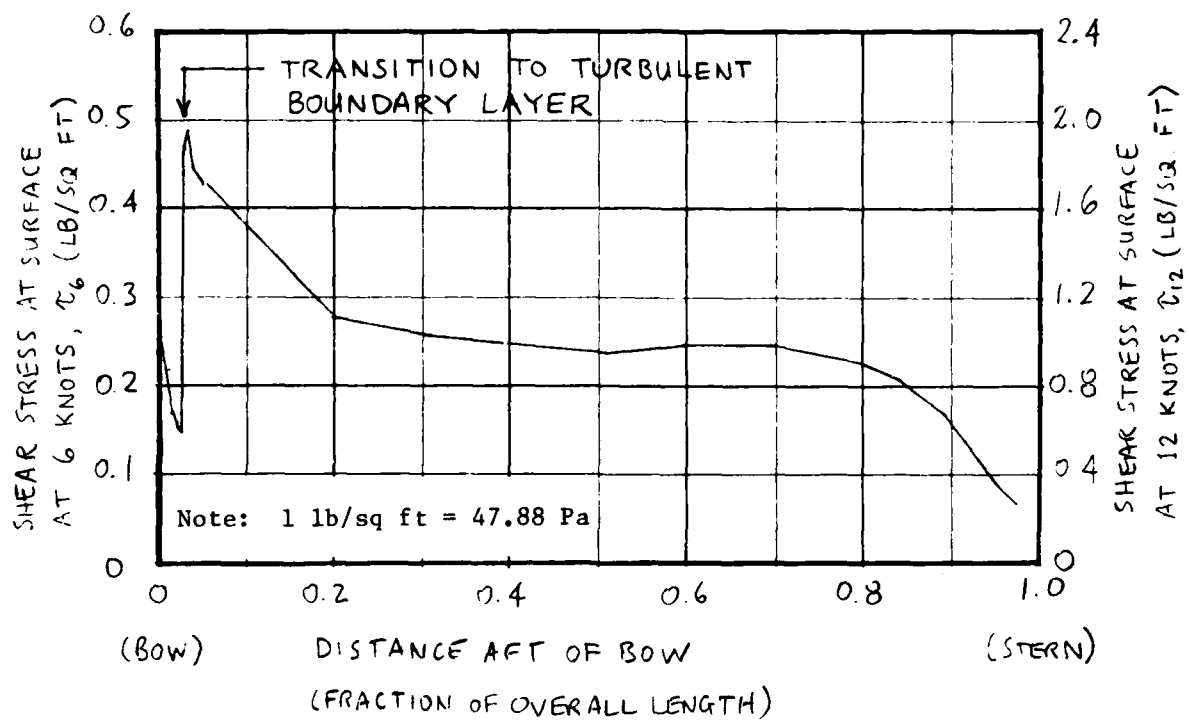


Figure 1b - Surface Shear Stress Distribution

from facility) or transient, i.e., reversible (changes with flow). Transient is preferred.

5. The technique must yield photographic patterns, in situ if transient.

ENVIRONMENTAL REQUIREMENTS FOR FV TECHNIQUES

The technique must function on the surfaces of models in hydrodynamic facilities under at least some of the conditions described below.

1. Models are immersed in water flow under mounting arrangements which often involve long periods of time (up to 2 hours) to remove from the water. The models are

- (a) suspended beneath towing carriages, at depths of zero to 35 ft;
- (b) in closed circuit water tunnels, at gage pressures from -1 to +4 bar;
- (c) from 1 in. to 30 ft in streamwise length;
- (d) operated at speeds from 1 to 50 knots with principal interest directed toward large models at about 10 knots and small models at 20 to 50 knots;
- (e) either towed in a straight line or rotated as in propellers

2. Model surface shapes are not developable. The radii of curvature of surfaces to be visualized need not be infinitely small. Smoothness standards are available [1]; * hydraulically smooth may be required, or slight roughness may be tolerable, depending on application.

3. Introducing foreign substances into the facility water is discouraged, unless easy removal is possible and feasible.

4. Materials should be nontoxic and not a health hazard to test personnel.

5. If medium is semi-permanent, it must be quickly recyclable to permit continued testing.

*References are listed on page 37 .

EXISTING AND PROPOSED NEW TECHNIQUES

Existing surface FV techniques have been analyzed from the standpoint of parameter indicated, practical considerations, and deficiencies. Improved techniques were sought from among a large number of candidate technologies which offered promise of reducing or eliminating the present deficiencies. Both current and proposed new techniques are discussed in the following sections.

SKIN FRICTION DIRECTION

Oil Dots and Film

A summary of existing techniques known to the authors for indicating skin friction direction is given in Table 1. The technique of choice is clearly oil dots. The use of oil coatings or dots in water has been only recently described in the literature, although it has become well established at DTNSRDC. Work on propellers and to a lesser extent ship hull models has established that oil dots, in particular, are even more effective in water than in air. In water, in regions of relatively high skin friction, an oil drop elongates into an extremely narrow tail which may extend several inches downstream, as illustrated in Figure 2 [2]. The extension is usually terminated by a relatively large pigment particle which apparently has been dragged downstream until the supply of oil and/or pigment has been exhausted. These trails may be as small as 0.01 in. (0.25 mm) in width. Such trails also arise when a band of oil is applied, or flows prematurely, in a direction transverse to the flow of interest. The pigment particles emerge from the band and move downstream, producing a row of closely-spaced narrow trails. Oil mixtures used at DTNSRDC include 10, 30, or 90-weight motor oil with sufficiently large amounts of added pigment to make the mixture quite viscous. Pigments used are lampblack, titanium oxide, and fluorescently dyed powders.

The principal deficiency of oil dots is the tendency to respond prematurely to flow during acceleration to and, to a lesser extent, deceleration from, the flow condition of interest. Although misinterpretation of the resulting patterns can be minimized by observing the model during periods of changing flow, the tendency toward off-speed response clearly detracts from the technique's value.

TABLE 1 - Existing Techniques

<u>Quantity</u>	<u>Type</u>	<u>Deficiency</u>
Skin Friction Direction		
Oil dots, oil film	Permanent	Premature response
Lead-acid paint	Permanent	Low resolution Recycle time Safety
Tufts, minitufts	Transient	Low resolution
Flow flags	Transient	Low resolution
pH paint	Transient	Low resolution
Skin Friction Magnitude		
Oil dots, oil film	Permanent	Resolution Premature response
Oil film interferometry	Permanent	Longevity in water
Pressure		
Reactive laminate	Permanent	Limited range



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To overcome this deficiency, some form of triggerable coating was initially sought which would respond to a remotely generated stimulus, after flow had become established. No coating material was found which could be successfully triggered by a practical physical effect.

Subsequently, various methods were proposed of producing skin friction patterns that would develop very slowly. In this way, only a small part of the pattern would be produced during flow changes, at the minor expense of a slightly longer run time. Four techniques were identified: very high viscosity fluids, delayed release capsules, slowly erodable coatings, and a slowly changing surface material. As listed in Table 2, several materials were selected for evaluation.

Lead-Acid Paint

Lead-acid paint is a method of producing permanent streaks along skin friction lines on painted model surfaces; the technique is detailed in the Appendix. This approach involves handling of extremely noxious chemicals and the use of lead-based paint, both of which are undesirable (the paint may not be available in the future). Its use is apparently limited to DTNSRDC.

Unfortunately, no replacement for this technique has been found which eliminates the chemical problems. Since the alternative permanent technique is oil dots, it is suggested that oil be injected through the ports otherwise used to inject acid. In this way the problem of oil's premature response would be avoided.

Tufts and Minitufts

Tufts give a fairly well-resolved coverage of surface skin friction direction when applied in large numbers as minitufts. Although originated by Crowder [3] for use in air, minitufts have more recently been used in water by Steinbring and Treaster [4] and at DTNSRDC. The Steinbring and Treaster paper presents many helpful suggestions for employing minitufts in water.

To improve the resolution of tufts, a more dense covering of even smaller tufts was proposed. Other approaches to improved resolution are

TABLE 2 - Candidate New Approaches

<u>Deficiency</u>	<u>Method</u>	<u>Candidates</u>
Premature Response	High viscosity fluids	3 fluids
	Delayed release capsules	1 capsule
	Slowly erodable coating	1 paint
	Slowly changing surface	2 metals
Low Resolution	Smaller tufts	1 fabric
	Dye sheet	1 electrode
	Dye tablets	1 tablet
	Liquid crystals	
	Thermal	1 sheet
	Shear-sensitive	1 liquid
	Compliant coating holography	foam
	Compliant coating speckle	foam

listed in Table 2. All techniques proposed would employ either a large number of very small active elements, or a coating which would yield continuous, high-resolution patterns.

Flow Flags

Flow flags are miniature rudder-like vanes supported on shafts which penetrate a model hull through special fittings. Pointers on the inboard end of the shafts are used to read orientation angles visually and record them manually. Fabrication of these devices is described in DTNSRDC drawing E-1407-1 entitled "Bilge Flow Flags." The cost of installation, effort in recording data manually, and relatively low resolution make these indicators rarely used in recent times, except for alignment of lifting surfaces such as submarine bowplanes with off-body flow. Improvements in resolution would require installation of a larger number of flags, or shifting to a different technique, as given in Table 2.

pH Paint

A promising technique involving a pH-indicator paint has been developed by Hoyt [5]. Transient colored streaks are left on the painted surface aft of ports from which a basic solution is injected.

It is noted that this technique, as represented by the phenolphthalein mixture, is quite effective in many ways.* Both transition and separation regions can be observed. Some indication of flow off of the surface is also obtained, as a result of colored streams emanating from particles of phenolphthalein embedded in the paint. These streams are smooth in laminar regions and irregular in turbulent regions. The paint coating is said to have negligible effect on drag, based on a number of experimental comparisons. Also, the indicator-containing paint remains effective for subsequent experiments conducted even years later (although color traces vanish when injection stops and must be photographed during testing). In view of these excellent characteristics, this technique is probably underused, perhaps because of ignorance of it.

Since low resolution is the principal deficiency with this technique,

*Hoyt, J.G., private communication

it was hypothesized that improved resolution could be accomplished by injecting the basic solution from a continuous slit or a flattened tube containing a series of small holes. Other approaches to improved resolution are as listed in Table 2.

Other Proposed Techniques

Other approaches to improving resolution of skin friction direction which were identified for further investigation included electrolytic generation of a dye sheet, and use of small dye tablets at many points on a surface.

SKIN FRICTION MAGNITUDE

Oil Dots and Film

Some indication of skin friction magnitude, in relative terms, is obtainable from oil patterns. However, interpretation of oil streak lengths and eroded oil film regions yields little resolution of differences in skin friction. An improvement in this regard would require a coating which would, for example, lose part of its thickness in a highly detectable manner. One proposed approach for such a technique was an erodable paint, which could be applied in thin, different-colored layers. A second, existing approach for such a detailed thickness measurement is described in the following section, but was not found feasible for use in typical facilities.

Oil Film Interferometry

Use of a thin oil film to indicate skin friction magnitude by interferometric measurement of thickness, developed by Tanner in air, has also been shown to work successfully in water [6]. This work also described applicability of the technique to curved surfaces, three-dimensional flow, in pressure gradients, and under the effect of gravity (all in air). Generally, the technique can be corrected for the various flow complications, but it was found that the oil film must be inserted quickly into the water flow, and removed within a minute or two, or it begins to disintegrate. Furthermore, interferograms may not be possible while the coated

surface is submerged; reported results were based on surfaces removed from water. Consequently, this technique may not be feasible for in-facility use, since model removal is not quickly accomplished.

The oil-like fluid used by Tanner was silicone fluid. Successful application of the basic approach, although hindered by the interaction between this fluid, the water, and the model surface (which had to be water-repellent), might be possible using a different indicating fluid or a different liquid flow medium. No evaluation or further development of this technique was pursued in the present work.

Other Proposed Techniques

Additional techniques proposed by the authors for improved resolution of skin friction magnitude were liquid crystal coatings (shear-sensitive and temperature-sensitive) and compliant coating speckle photography. These techniques may be feasible; further discussion is given in a later section.

PRESSURE INDICATORS

The only known pressure-distribution-indicating coating has been described by Okitsu and Aoki [7]. A laminated sheet containing two colorless chemical reactants which become red after reacting was used. One of the reactants was encapsulated in capsules which were broken by high pressures produced by cavity collapse on a cavitating propeller or turbine blade. The laminated sheet was cemented to the blade surface. Detailed measurements of color intensity were used to estimate cavity impact pressure distributions. This material requires relatively high pressures for activation, on the order of 20,000 to 200,000 psf (980 to 9800 kPa).

The extraordinarily high pressure range in which this material acts makes it not feasible for subcavitating flow experiments.

Another possible visualization material is pressure-sensitive liquid crystal. However, consultations with chemists indicated that liquid crystals sensitive to pressure are effective only at very high pressures. Thus no candidate material was found.

One optical method, holographic interferometry of compliant coatings, was identified as a candidate for high-resolution of pressure distributions on model surfaces.

EVALUATION OF CANDIDATE TECHNIQUES

Several of the candidate techniques were evaluated by performing a simple experiment which used the technique to visualize flow around a simulated model. The model consisted of a right circular cylinder 2.5 in. (64mm) in diameter and 6 in. (152 mm) high fastened to a 12-in. (305-mm) square plate (see Figure 3). The plate was placed at the bottom of a tank 3 ft long by 2 ft wide by 2 ft deep (914mm x 610mm x 610mm). A water jet was directed at the plate just forward of the cylinder. Water jet speeds ranged from 3 to 62 ft/sec (2 to 37 knots). The various FV techniques were applied to the plate or the cylinder.

Other techniques, notably the optical and liquid crystal approaches, were evaluated only in terms of estimated feasibility.

Results of these evaluations are given in the following sections.

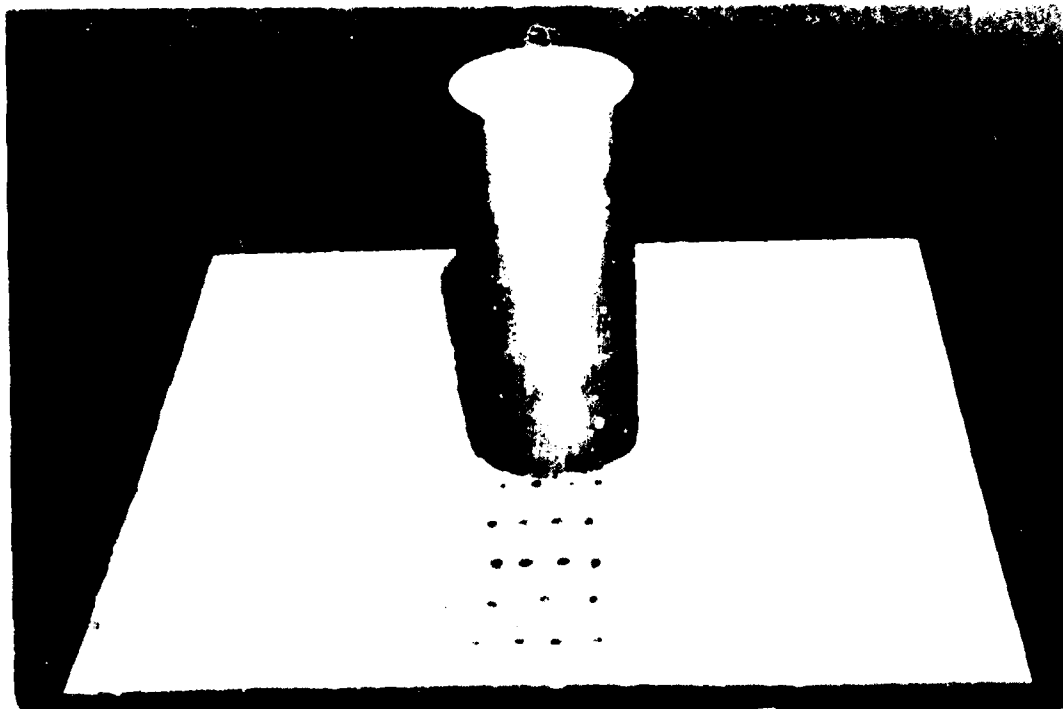
APPROACHES FOR DELAYING RESPONSE

HIGH-VISCOSITY FLUID DOTS

Although dots of pigmented oil function very well in water, improvement is desired in formulating a fluid which will not run prior to reaching the flow condition of interest. No strategy for achieving this goal based on generating a stimulus which would activate a FV medium upon command was found by the authors in discussions or the literature. As a substitute, it was decided to evaluate experimentally several different high-viscosity fluids in the hope that some would develop an elongated dot pattern more slowly than oil. In this way, a larger proportion of the fully developed pattern would be valid.

The fluids used are listed in Table 3. It will be noted that the approach emphasized use of fluids which were inherently of high viscosity, in contrast to the conventional mixture of a relatively low-viscosity oil mixed with a large amount of powdered pigment which produced a mixture of varying (unspecified) viscosity up to a paste-like substance.

The evaluation was done by placing dots of the various fluids on the flat plate and around the cylindrical model. The plate and cylinder were



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Figure 3 - Hydrodynamic Model Showing Aft View of Sill
Fluid Dot Pattern Produced with Water Jet.

TABLE 3 - Fluids Used For Dots

<u>Type of Fluid</u>	<u>Designation</u>	<u>Added Colorant</u>	<u>Viscosity</u>
Gear Oil	Product O-1	None (Black)	approx. SAE 250
Petroleum-Based Greases	Product G-1	None (Red)	very high
	Product G-2	Red Dye (Product D-1)	intermediate
	Product G-3	Red Dye (Product D-1)	intermediate
	Product G-4	Red Dye (Product D-1)	intermediate
Silicone Fluids	Product S-1	Red Dye (Product D-1)	1,000 cs
	Product S-2	Red Dye (Product D-1)	10,000 cs
	Product S-3	Red Dye (Product D-1)	100,000 cs
Epoxy Resin	Product E-1	Red Dye (Product D-1)	intermediate
Conventional Motor Oil*	Non-detergent Motor Oil	Carbon black powder	low to very high
	(SAE 10 to 90)	Titanium oxide powder Fluorescent pigment powder (9 parts oil, 1 or more parts powder by weight)	

* As typically used at DTNSRDC. This material was not specifically evaluated as part of the present work.

coated with medium gray enamel paint. The water jet was used to produce dot elongation. The average jet speed ranged from 2 to above 16 knots.

A wide variety of characteristics was exhibited by the five petroleum products. Product O-1 was a moderately high-viscosity gear case oil (approximately SAE 250) which was applied to the model straight out of the can (without dye) as it was black in color. In general, this material was deemed unsatisfactory, for while it gave adequate flow indication at low flow speeds (under 15 knots), it tended to separate from the model and contaminate the basin water at higher speeds. This material also splattered around the cylinder and was extremely difficult to remove from the model. In general, this was a very messy material and of limited value in flow visualization work.

The first of the four greases, Product G-1, was an extremely viscous red-colored grease which was easier to work with than the gear oil. This material was so viscous that dots of the material up to one-half inch (13mm) in diameter did not run under the influence of gravity. Because of the high viscosity, dots of this material formed elongated streaks only in high speed flows (greater than 24 knots). However, dots of the material when streaking did not tend to neck down but rather smeared back in a streak as wide as the diameter of the original dot. Dots located in separation zones showed a characteristic wedge-shaped cross section which might help to locate the exact point of separation. This material has the additional advantages of being nonpolluting due to its good adhesion, is already colored, and is extremely easy to remove from the model.

The second grease, Product G-2, had a lower viscosity than Product G-1 but a higher viscosity than the gear oil. Product G-2 was colored red by adding an oil soluble dye, Product D-1. This material did not display good adhesion, and at flow velocities above 15 knots, tended to separate from the model and pollute the basin water. At low speeds (between 3 and 10 knots) it gave good flow indications and was very easy to remove.

The third grease, Product G-3, was also slightly less viscous than Product G-1. This material, naturally a light tan color, was also dyed red by adding Product D-1. Among the petroleum-based products tested, this material gave the best results. It left good flow indications which tended to thin down into sharp downstream points and did not pollute. Cleanup was also easy.

The fourth and final grease evaluated was Product G-4, described by its manufacturer as a rheopectic grease. At low speeds this material flowed readily, separating from the model and polluting the basin. In fact, at low speed, Product G-4 was the worst-polluting material tested. At higher speeds (above 17 knots), the material's rheopectic action apparently increased its viscosity in response to the increased shear, since the substance became more adherent to the model surface (and thus less polluting). The quality of the flow indications also improved.

These results indicate that some optimum form of grease possibly could be formulated which would produce well-tapered (oil-like) streaks, operate satisfactorily at low and high speeds (with different viscosities perhaps required), resist dispersion into the water flow, and wash off easily with detergent. An approximation to this material is provided by the best-performing grease, Product G-3. Effective colorants in many hues are readily available. Thus, the basic premise that a fluid of naturally high viscosity, rather than of high viscosity artificially induced by added pigment, may be an effective flow visualization fluid is at least partially substantiated.

Silicone fluids exhibited much less variability in behavior than the greases. These fluids differed only in viscosity; all were transparent, colorless, caused no visible pollution (no detailed analysis of water samples was made) and easily cleaned off the painted surface. A significant problem was encountered, however, in trying to add coloring to the lower-viscosity fluids, Products S-1 and S-2. After trying many intensely colored pigments (which settled out) and dyes (which were generally immiscible), a pale coloration was produced with the red oil-soluble dye, Product D-1. Unmixed dye globules were filtered out. The resulting color was quite pale and not suitable for general testing. The highest-viscosity fluid, Product S-3, was readily colored using any of the pigments, since settling of the pigments occurred extremely slowly.

Tests of these fluids, along with the greases, showed that viscosity was the factor that determined the shape of streak formed when a dot elongated under flow. The 1000 cs fluid formed streaks with tails which tapered inward rapidly and then became very long; the edges of the tails were concave. An example of a dot pattern produced with 1000 cs fluid is shown in Figure 3; the dots are pale pink on a light gray painted surface and

have concave edges. In contrast, the 10,000 cs fluid formed much shorter tails which had convex-shaped edges. In some cases, the more viscous fluid tails flowed downstream with little or no tapering at all. The 100,000 cs fluid was nearly immobile under the flow velocities used. However, what elongation took place was not tapered. It is apparent that the viscosity range needed for typical experiments is between 1,000 and 10,000 cs.

Since narrow-tailed streaks provide the most accurate indication of skin friction (shear stress) direction, these results suggest that the lowest-viscosity fluid possible, consistent with other requirements, should be used in a given experiment. Greater resistance to premature flow requires a higher viscosity. Additional experimentation is required to determine whether fluid that is resistant to premature flow is of sufficiently low viscosity to form narrow-tailed streaks. In seeking this answer for a given flow regime, it appears that the shape of the streak (concave, convex, or straight edges) can be used to determine what effect changes in viscosity will produce.

Silicone fluid lends itself particularly well to changing its viscosity. It is available in an extremely wide range of viscosities, from 0.65 to 600,000 cs. Different grades of fluid can be blended to make a mixture having any desired viscosity over this range.

Unfortunately, no effective means of coloring the silicon fluids of viscosity 10,000 cs and below has been found. A solution to the dyeing problem may make this material extremely useful for oil-dot experiments.

Another type of fluid - epoxy resin (without hardener) - was also evaluated as a surface flow indicator. This material, Product E-1, was a relatively high-viscosity fluid, although some of lower viscosity are available. The results were similar to those for petroleum greases in terms of flow indication, and the resins were not noticeably polluting. However, the resin was impossible to clean off the painted model surface without damaging the paint. Consequently, it is recommended that epoxy resins not be used for flow visualization work on painted models. Removal testing was not performed on metal and fiberglass surfaces.

ENCAPSULATED OIL

As an alternative approach to avoiding premature flow of oil or fluid

dots, a method was sought for releasing a small quantity of marker fluid after sufficient time for the ambient flow to reach full speed. The method would have to consist of a small attachable "package" comprising a small amount of marking fluid within an enveloping membrane which could be breached by some time-delayed action. Alternatively, some intrinsic property of the fluid might be exploited.

Two problems presented themselves: how could the triggering be accomplished, and would the marking fluid adhere to and thus mark the model surface. After considering triggering methods such as laser beams and pressure impulses, it was decided to simply employ a gelatin capsule which would rupture after sufficient softening was caused by water immersion. Pharmaceutical gelatin capsules (No. 0 blue) were found to soften partially after 2 min of immersion in room temperature water. Further softening followed but the capsules did not dissolve. Thirty-six halves of these two-piece capsules were filled with oil-soluble dye (Product D-1) and glued to the flat, painted model surface using RTV silicone rubber adhesive. The plate was held upside down during this step to avoid spilling the dye.

A flow experiment was conducted on the capsules as follows. Several capsules were pierced on the top or at two locations in the base; others were not pierced. After a half hour of soaking in still water, the water jet directed at the model cylinder was turned on. The first capsule ruptured and released all of its dye after 40 s; all capsules had ruptured and the experiment was ended after 30 min.

The performance of the capsules as flow markers was extremely poor. Of the 36 capsules, only 3 or 4 produced an obvious aft-trailing streak of dye; the others released the dye with a smudged or no effect on the model surface. There was a greater tendency for capsules with holes in the base to mark the surface. It should be noted that the dye used was quite buoyant, so that there existed a strong tendency for the dye to rise away from the model surface. Future efforts of this type should employ a neutrally buoyant dye. Other deficiencies of the technique were also apparent. The capsules acted as large protuberances on the surface before and after releasing the dye. Dye leaked from the capsules before and during the experiment, polluting the water.

It is concluded that fluid released in this manner may produce some marking of the surface. However, the technique as tested is not usable.

ERODABLE PAINT

This type of paint is used on submerged ship hulls for antifouling protection. It is said that the material softens and sloughs off small amounts from its surface when exposed to flow, and observations of eroded areas on ship hulls were mentioned to the authors. Such behavior could produce a permanent marking of high-skin-friction areas such as found on propeller blades if the paint were applied in thin layers of different color.

Consequently, an aluminum plate was brush-painted with four layers of different-colored erodable antifouling paint. A high-speed (37 knot mean velocity) water jet was directed against the plate. After 200 hr no visible change in surface appearance had occurred. It is concluded that this paint as presently formulated is not suitable for experiments conducted within the usual towing tank time constraints, although some specialized applications might exist.

SLOWLY SOLUBLE CHEMICALS

A number of chemical coatings have been used in the past to provide a white film which is slowly removed from a black-colored surface due to solubility of the coating in water. Coating removal proceeds more rapidly in turbulent boundary layers than in laminar ones, enabling transition regions to be determined. Regions of high shear stress such as occur around appendages would also be indicated by this method.

The following chemicals have been employed in this method:

Acetanilid in acetone [8] - used at up to 2.74 m/s (5.3 knots)

Acetanilide [9, 10] - limited to below 3 m/s (5.8 knots)

Acentanilide plus dibutyl phthalate [9, 10] - limited to below 3 m/s (5.8 knots)

Hydroquinone diacetate plus acetone [9, 10] - above 3 m/s (5.8 knots)

Acetoacetanihide [9, 10]

Exalgin [9, 10]

Para-acetotoluidide [9, 10]

Benzoine [9, 10]

Stearic acid [9, 10]

Benzoic acid [8] - used at 1.5 m/s (2.9 knots)

As noted by Thompson [9], chemicals used in this manner are not suitable for use in flow facilities which require a model to be immersed for several minutes before on-speed operation, since the chemicals will be partially or wholly removed during the waiting period. For this reason, such materials do not satisfy the requirement for use in typical model installations.

METAL CORROSION OR EROSION

It is known that surfaces of active metals become oxidized or otherwise corroded under moist conditions. The corrosion might occur in a pattern which reflects shear stress distributions, depending on the chemistry and surface physics involved.

This possibility was tested using a silver surface plated on a copper sheet, upon which was placed the 2.5-in. (64mm) diameter cylinder previously described. The cylinder/plate model was exposed to a high-speed (37 knot velocity) water jet impinging on the plate about 1 to 2 cylinder diameters forward of the cylinder. The water jet was operated for about 66 hr. After 6 hr, no effect was visible, but after 66 hr all silver in the jet impact area had eroded away, exposing copper. Examination of the area around the cylinder, where some indication of a protuberance-induced wake flow would be desired, showed a barely perceptible, symmetrical pair of irregular shapes which were presumably left by the wake pattern. The shapes were apparently weakly eroded regions, since some copper color showed through. Visibility was improved when viewed at a low angle with strong lighting. However, the observed pattern faded to some extent over a period of days following the experiment. Thus, long-term permanence would not be expected unless a very high contrast pattern was present initially.

It is concluded that both the length of time required for production of a pattern and the low contrast of the pattern obtained show that neither corrosion nor erosion of silver or copper is a feasible flow visualization technique.

APPROACHES FOR HIGHER RESOLUTION

LIQUID CRYSTAL COATINGS

Liquid crystals have been described as the most optically active form of matter [11]. As such, their properties must be considered as a potential source of surface flow visualization, especially since only a microscopic layer of the material is required. Among the many physical effects which produce optical changes in liquid crystals are temperature and shear stress. Both of these effects have been used for flow visualization in air flow. However, no successful applications of liquid crystals in water flow have been reported. The principal difficulty lies in producing a coating which remains sensitive to its activating parameter while being water-resistant.

Two approaches have been tried to produce a water-resistant coating. Both employed temperature-sensitive liquid crystal that was encapsulated. The first was reported by Stinebring [12] in which he attempted to waterproof a layer of gelatin-encapsulated liquid crystal by spraying various clear coatings over the layer. These coatings remained intact for up to one day but none was permanent.

The second approach involved covering a film of liquid crystal (which is of oil-like consistency) with a waterproof plastic sheet. The present authors employed a commercially available liquid crystal sheet of that design, which was sensitive to temperature. The sheet of liquid crystal successfully withstood water immersion, but was of little use for flow visualization. The sheet was placed on a flat plate beneath the cylindrical model and subjected to a jet of warm water. Definite colored regions of temperature differential appeared around the cylinder. However, the aluminum model warmed up with time and caused the temperature pattern to fade. The requirement for water of a different temperature from the model is also a tremendous disadvantage, although a heated model might provide a feasible approach.

For models which cannot be heated effectively, some method of applying a coating of liquid crystal which is sensitive to shear stress or pressure is required. Shear-sensitive liquid crystals have been evaluated in air flow by Klein and Margozi [13]. Color changes with shear were produced, but the liquid formed wavelets which interfered with laminar flow and clarity of observations. For protection from water, the material must be

either covered by a coating which does not interfere with shear or pressure sensitivity, easy enough for pressure but almost impossible with shear, or converted into a solid which retains the liquid crystal property. This latter process may be more correctly viewed as finding or producing a solid, optically active material with shear or pressure sensitivity.

Although this survey was unable to discover any liquid crystal coating which would be feasible for unheated surfaces in water, it is recommended that further research be undertaken to exploit the extraordinary optical properties of liquid crystals. Approaches involving innovative water-resistant packaging of shear and pressure-sensitive liquid crystals of appropriate sensitivity, as well as conversion of liquid crystals into water-resistant forms, should be pursued.

SOFT OPTICAL COATINGS

Several optical methods such as holography are available which can measure extremely small displacements of solid surfaces. These methods are typically used to study vibration modes of complex structures, or to measure the location of various surfaces in two- or three-dimensional space. However, a further application might be to measure or visualize deformation of a soft coating on a hydrodynamic model surface, where the deformations are produced by shear stress or pressure caused by water flow.

A survey was made of optical techniques which might be effective in the above manner. Three techniques were identified: holography, speckle photography, and photoelasticity. Each is discussed in the following sections.

Compliant Coating Holography

Holography employs coherent laser light to measure all three components of the displacement vector on the surface of an object. By way of definition, if one were to photograph a model, the in-plane displacements would be in the film plane while the out-of-plane component would be normal to the film. Holography is most sensitive to the out-of-plane displacement. If all of the displacement was out-of-plane, each fringe in the holographic image would correspond to a line of constant deformation with a sensitivity of about 10 μ -inches between fringes. When in-plane displace-

ments are also present, the fringe pattern is complex and must be evaluated on a point-by-point basis.

Pressures could be measured holographically by first coating the model with a soft material which would deform locally in proportion to the applied pressure. With this predominately out-of-plane deformation, a contour map of surface pressure could be obtained. Figure 4 is a plot of the dynamic pressure required to obtain a good fringe pattern, about eight fringes, as a function of coating thickness for four different values of compressibility. These values are about two orders of magnitude above those of most rubber-like polymers. Consequently, air-entrained closed-cell foam materials must be used to obtain a sufficiently high value of compressibility.

Although the sensitivity of holography is adequate to measure pressures down to 100 psf, it has the disadvantage that rigid body motions and body deflections due to the applied loads cause displacement components to be superimposed on the coating deformations, possibly resulting in an unresolvable fringe pattern. The extreme sensitivity of holography makes it crucial to restrict body motions and deflections to very small values.

Compliant Coating Speckle Photography

Speckle refers to the grainy-looking random fringe pattern produced when an unpolished surface is illuminated with laser light. Two displaced identical speckle patterns can be used to measure, primarily, in-plane displacement components. Out-of-plane measurement techniques have been proposed but not utilized because the resulting fringe patterns are of generally poor quality in air and are likely to be worthless in underwater applications, where conditions are less favorable than in air. Therefore, speckle is not a good candidate to use in measuring pressures by the previous coating method.

Since speckle photography is most sensitive in measuring in-plane displacement, it can be used to determine shear stresses on a model. Although speckle is somewhat less sensitive than holography, it is easier to convert the fringe data to displacements. Speckle is also less sensitive to rigid body motion than holography and is therefore more often utilized outside of the laboratory. It is nevertheless a coherent, optical

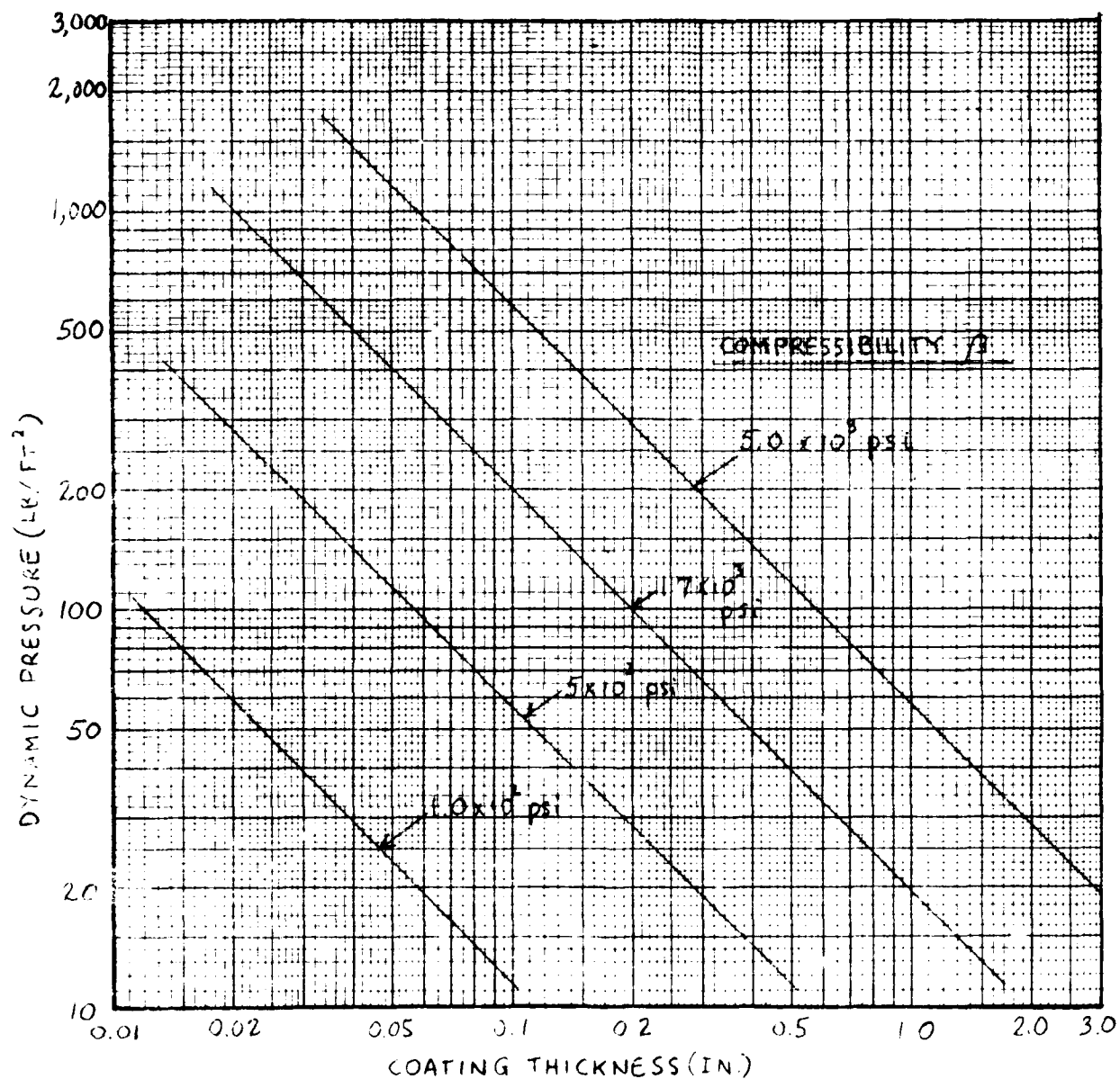


Figure 4 - Dynamic Pressure on Model Surface as a Function of Coating Thickness for a Compression of 80 μ in. (8 Holographic Fringes)

technique and therefore subject to restrictions on unwanted body motions.

It is believed that closed-cell foams are required to produce detectable speckle fringes, as for holography, but no estimates of required material properties have been made.

Compliant Coating Photoelasticity

Photoelasticity is a non-coherent, polarized light technique that makes use of the birefringent nature of certain materials to determine their state of stress. Materials such as polyester and polyurethane are birefringent materials suitable for use as coatings. Unfortunately, a calculation of the hydrodynamic pressure required to produce one interference fringe showed that the required pressure is much larger than will occur even on high-speed models. Since photoelastic observations require a transparent material, the compressibility of the coating can not be increased by air entrainment. Therefore this technique can not be used as a means of visualizing pressure. In view of the low shear stresses produced in typical flows, it appears likely that shear stress visualization will also be impossible. Consequently this technique should not be pursued.

Experimental Requirements

The use of any of the optical techniques presupposes an unobstructed view of the model. Further, the water must be clear enough to permit sharp photographs of the model's surface. Bubbles and suspended particles must be avoided as much as possible.

Laser illumination of large models under water presents a particular problem. A narrow-diameter laser beam must be expanded to the required field of view using a diverging lens. Refraction of the laser light as the beam enters the water from the lens tends to reduce the angle of divergence, so that a larger standoff distance is required in water (as compared to air). However, light absorption by water increases rapidly with distance. Therefore, unacceptably long exposure times might be required for large models. For reference it is noted illumination of a model surface 4 to 5 ft (1.2 to 1.5 m) in width would require a standoff distance of at least 6 ft (1.8 m).

The coherent light techniques require the use of fairly high power lasers (Class IV). Safety regulations require that they only be used in restricted areas so that passersby cannot see the laser light. This generally requires the construction of enclosures with interlocks on the entrances to terminate the light.

Elimination of rigid body motion of towed models would probably require a relatively rigid platform which moves along with the model through the water and carries the optics. Models mounted at a fixed position in water tunnels may be more resistant to unwanted deflections.

The evaluation of a propeller spinning at several hundred rpm in a water tunnel is a considerably more challenging problem. An image derotator device offers perhaps the best hope for evaluating rotating objects using coherent optical methods. Image derotator systems effectively freeze the image of the propeller and have been used with both holography and speckle to measure transitory phenomena on turbine blades rotating in air.

When the pressure is large enough to deform (or stress) the soft coating on a lifting surface such as a propeller blade, it is most likely large enough to deflect the blade so that the coating deformations (stresses) would be superimposed on the blade deflections (bending stresses) with the resulting fringe patterns becoming unresolvable. In any event, a strength analysis of the propeller blade would need to be done to determine the feasibility of measuring pressures on it.

Discussion of Optical Techniques

Holography appears to be sensitive enough to be used in pressure measurements if the problems with rigid body motions can be overcome. Although holography can also be used to measure shear stresses, speckle techniques are easier to use and to evaluate. Both holography and speckle suffer from the safety regulations needed for lasers.

It appears that the most feasible application of optical techniques would be the use of laser speckle to measure shear stress on a model rigidly mounted in a water tunnel. Research is required to identify suitable soft coatings; air-entrained closed-cell foams are good candidates because of their high compressibility.

It also appears feasible to determine a pressure distribution

holographically. In this instance extreme mounting rigidity is essential; model movement probably is the greatest obstacle to a successful application.

ELECTROLYTIC DYE SHEET

Electrolytic production of densely colored fluid is in principle a useful method of injecting "dye" into a flow field. The electrode at which the colorant forms could be embedded flush with a model surface, emitting a sheet of dye from an elongated element. Varying current supplied to the electrode could vary the amount of dye to compensate for different flow speeds, visibility, etc. High resolution of boundary layer phenomena would be obtained from continuous sheets of dye emanating from a series of electrodes.

Two methods have been reported which produce suspensions of minute colored particles from solid surfaces. The first [14] uses metallic tellurium as a cathode from which emanates a dense black cloud of suspended tellurium particles. The second method [15] produces a white cloud of precipitated particles produced by electrolysis of a solder-covered brass cathode. For both methods, a significant limitation was expected to be the relatively low rate at which colored fluid could be produced. In prior applications, very low speed flow was employed.

This limitation was obvious in the present study, in which the tellurium method was evaluated. When pieces of tellurium were connected to a 24 v potential, black dye was generated. This dye flowed upward in response to convection produced by the metal connector in contact with the tellurium. However, a water current of even a knot or two carried away the dye faster than a visible trace could be produced.

It is concluded that electrolytic production of dye is not feasible for moderate to high speed water flow research.

EXTREMELY SMALL TUFTS

To improve the resolution offered by even closely-spaced minitufts, the authors conceived of a dense, carpet-pile-like coating of flexible elements or microtufts which would deflect in the direction of the local skin

friction. The term microtuft is used to imply a shorter, more closely spaced type of tuft than for minitufts, which in water tunnel applications [4] have consisted of nylon filaments 0.5 to 0.75 in. (12.7 to 19.0 mm) in length and spaced perhaps one tuft length apart. The elements would have to be visible under lighting so that photographs could be made of the flow-induced patterns.

No suitable existing material was found. To perform a crude evaluation of the concept, long-napped black velvet fabric was exposed to a water jet. The resulting appearance of the fabric showed no visible indication of flow direction either by naked eye or in photographs. The fabric nap, which had a visible orientation when dry, lost all surface detail when wet.

It is concluded that no suitable microtuft material is known at this time. Viewability based on light reflection from the tuft surfaces may be difficult to achieve underwater.

DISCUSSION

Of the various approaches described for either producing a delayed response to flow conditions, or producing higher-resolution patterns, only three have potential as improved FV techniques. The techniques are listed as items 1, 2 and 3 in Table 4. The technique of most immediate practical significance is the use of newly identified fluids (grease and silicone fluids) for semi-permanent dot patterns. These fluids are homogeneous rather than a mixture of pigment and oil as in present use. Dye must be added for coloration. In the case of the silicone fluids, finding a suitable dye is a problem for future research. The improvement offered is the opportunity to tailor a dot fluid to the precise viscosity that will yield narrow dye trails at the speed of interest, yet not run at lower speeds. Fluid dots are particularly effective for research on hydrodynamic flow because both shear stress direction and magnitude are indicated to some extent.

The second type of technique, optical coatings, represents two methods of indicating shear stress and pressure, but has yet to be demonstrated. The need for a soft coating on a model should be easily met. Ideally, a soft material would be sprayed on or brushed on and allowed to cure before

TABLE 4 - Proposed New Surface Flow Visualization Techniques

<u>Technique</u>	<u>Type</u>	<u>Speed Range</u>	<u>Shear Direction</u>	<u>Shear Magnitude</u>	<u>Pressure</u>
1. Fluid Dots					
Petroleum Grease	Semi-Perm.	Medium	Yes	Yes	~
Silicone Fluids	Semi-Perm.	All	Yes	Yes	~
2. Optical Coatings					
Speckle Photography	Transient	Medium	-	Yes	~
Holography	Transient	All	-	-	Yes
3. Liquid Crystal Coating*					
Shear Sensitive	Transient	N.A.	Yes	*	~
Pressure Sensitive	Transient	N.A.	Yes	-	*
4. pH Indicator Paint [5]	Transient	All	Yes	-	~
5. Minitufts [4]	Transient	All	Yes	-	~
6. Chemical Reaction [6]	Permanent	High	-	-	Yes

* Water-resistant liquid crystal coatings do not exist at present (see text). This category is included for conceptual purposes only.

testing. Some practical difficulties would remain, but a demonstration of the speckle photography method of visualizing shear stress distribution on a fixed model in a water tunnel appears readily achievable. If propellers were being studied, an image derotator would be needed for the two most promising techniques. These methods represent established optical technology; only the application, to reveal fluid flow over soft coatings, is new. The promise of obtaining a continuous, high-resolution shear stress or pressure distribution over a curved body by nonintrusive means makes these techniques worthy of development.

The ultimate in a flow visualization coating would be achieved if a water-resistant form of liquid crystal can be developed. Appropriately shear-sensitive forms are known, although pressure-sensitive forms are not. Successful application of this technology will require either innovative packaging techniques or production of new forms of the optically active materials. Advantages to be gained are operation with no special illumination or image derotation, extreme thinness of coating along with great sensitivity (unless packaging alters this feature), and direct indication by color pattern rather than fringe pattern (unless birefringent forms of liquid crystal are used). It is recommended that chemical means of converting liquid crystals to water-resistant forms be pursued.

Three additional techniques are included in Table 4. Methods 4, 5, and 6 have been successfully demonstrated and do not require further development before use. However, these techniques may not be widely known; this opportunity is taken to bring them to the experimentalist's attention.

CONCLUSION

Various types of technology not currently in use in surface flow visualization experiments may provide valuable new techniques for surface flow visualization. In particular, high-viscosity fluids for dot patterns, optical techniques using soft coatings, and liquid crystal materials or derivatives, offer excellent potential.

RECOMMENDATIONS

1. For fluids to be used for dots, experiments should be conducted to

establish the fluid viscosity needed for optimum streak production over various flow speed (shear stress) ranges.

2. A means of coloring silicon fluid should be developed.

3. A demonstration of shear stress measurement using speckle photography on a soft coating on a fixed model in a water tunnel should be carried out. A second demonstration should be performed of pressure measurement using holography with the same model.

4. Chemical and packaging studies to produce water-resistant forms of shear-sensitive liquid crystals should be conducted. Pressure-sensitive liquid crystals should be identified or developed.

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APPENDIX
LEAD-ACID PAINT TECHNIQUE

This permanent flow visualization technique requires injection of a specially prepared fluid so as to contact the surface of a model which had been coated with lead-pigment paint. White-colored paint is used. A dark brown streak is produced over a distance several feet downstream of the injection port.

Preparation of the injection fluid must be done in a well-ventilated area and by personnel wearing protective clothing. First, gaseous hydrogen sulfide (H_2S) obtained from pressurized bottles is bubbled through water until the water becomes cloudy. This solution is then mixed with hydrochloric acid (HCl) in a ratio of 4 parts H_2S solution to 1 part HCl .

It is believed that the brown stain produced when the fluid and paint react is lead sulfide (PbS), which remains fixed in the paint coating. Other by-products such as hydrogen, chlorine, and water disperse into the towing facility. The model must be repainted to produce a new pattern.

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