National Committee for Fluid Mechanics Films

FILM NOTES

for

FLOW VISUALIZATION*

By

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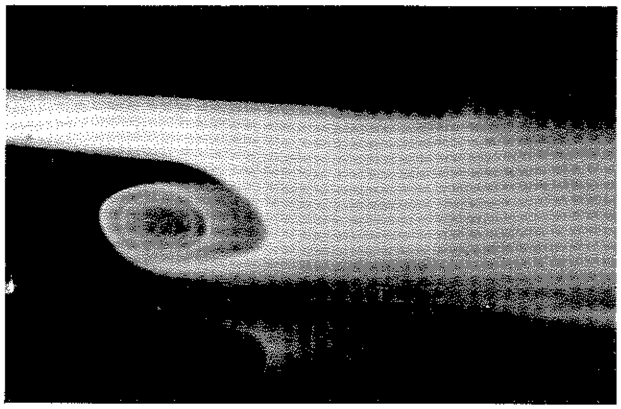
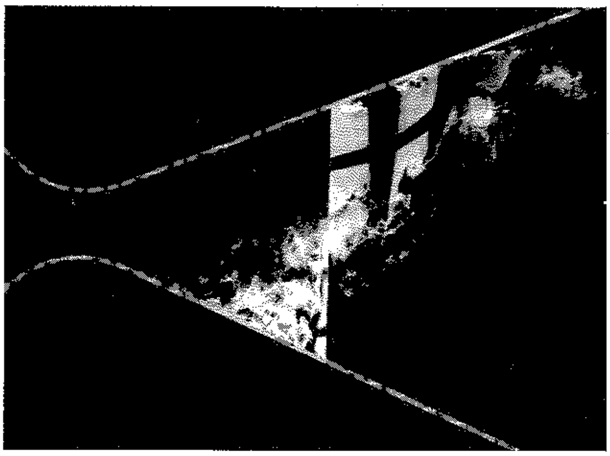
I. Uses of Visualization

Moving fluids often form patterns so complicated that intuition fails when we try to imagine them. Some flows are so complicated that we cannot analyze all their details from the governing equations, even with the biggest computers now available. Visual images of the actual flows (Figs. 1, 2, 3, 4) can advise us of the real flow patterns.



1. Boundary-layer flow in a symmetric strut corner (visualization by hydrogen bubbles).



2. Fully-developed stall in a diffuser (visualization by hydrogen bubbles).

In time-dependent flows, different flow patterns succeed one another, making it very difficult to obtain understanding of the flow phenomena from the output of a few probes at fixed locations. Various visual techniques can then be used as experimental tools for determining the general nature of a complicated flow

*FLOW VISUALIZATION, a 16-mm B&W sound film, 31 minutes in length, was produced by Education Development Center (formerly Educational Services Incorporated) under the direction of the National Committee for Fluid Mechanics Films, with the support of the National Science Foundation. Additional copies of the film notes and information on purchase and rental of the film may be obtained from the distributor:

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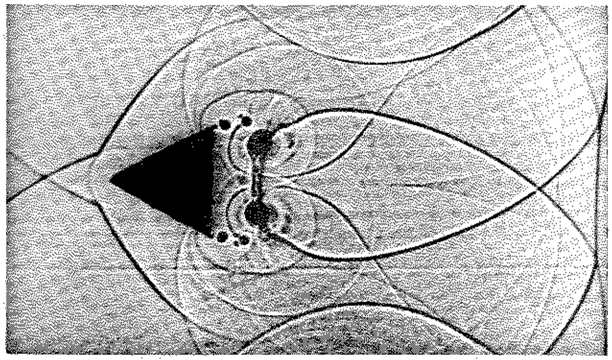
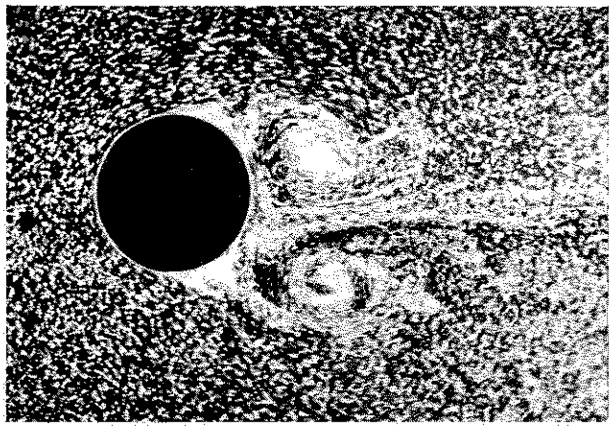


3. Transient shock pattern in flow over a wedge (shadowgraph visualization).

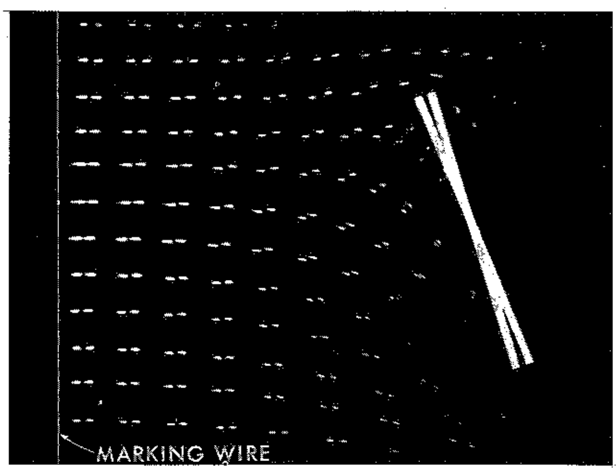


4. The wake of a cylinder visualized by surface powder.

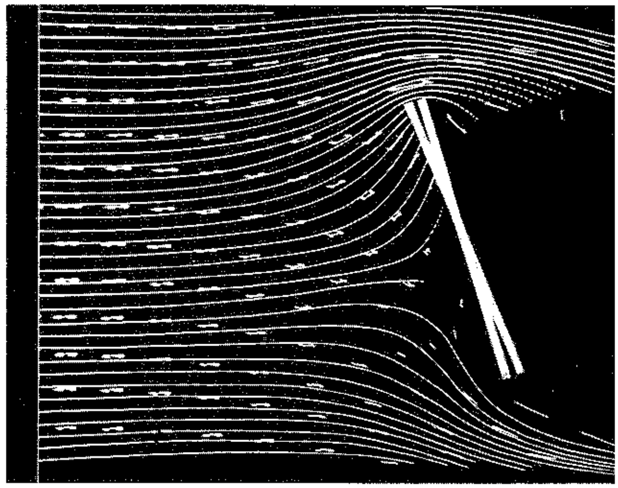
and also to provide quantitative measurements of such things as speed, frequency, density, time sequences, etc.

In a flow past an oscillating plate (Fig. 5), the motion is truly periodic; in principle, it could be constructed from point measurements if phase information were retained. Even so, construction from visual data, as in Figs. 5a and 5b, may be easier. In flows that are unsteady but not truly periodic, such as turbulent shear flows, the measurements are much more difficult. In such cases, motion pictures of the flow can be of great aid in perceiving the total flow structure, in finding instantaneous velocity profiles, and in determining the time sequences of events as a step in establishing causality. A good example is the sequence of Fig. 6, showing respectively laminar, transitional, and turbulent flow in a boundary layer on a smooth, flat surface.

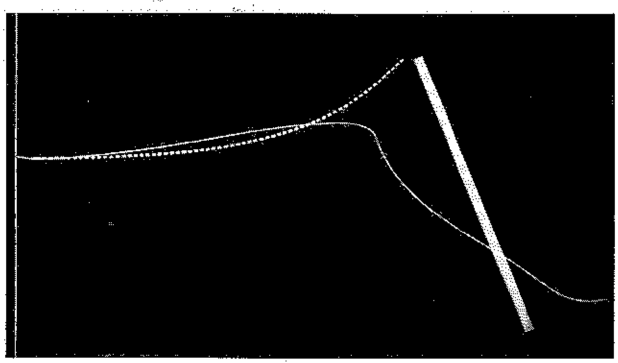
Many flows are very sensitive to small changes in geometry or in other boundary conditions; a small change in conditions may cause a very large shift in



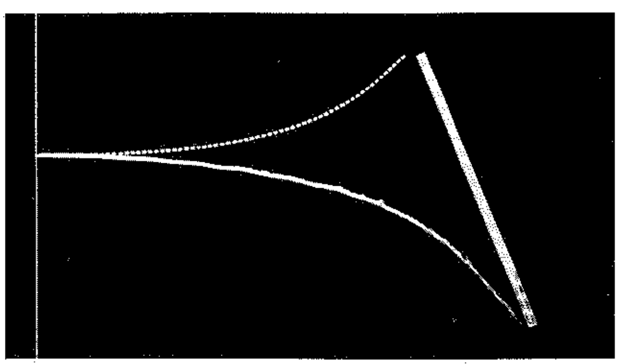
5a. Combined-time-streak markers in flow past an oscillating plate. Two frames a short time apart are shown superimposed.



5b. Instantaneous streamlines* for oscillating plate flow, determined from the velocity-direction field of Fig. 5a.



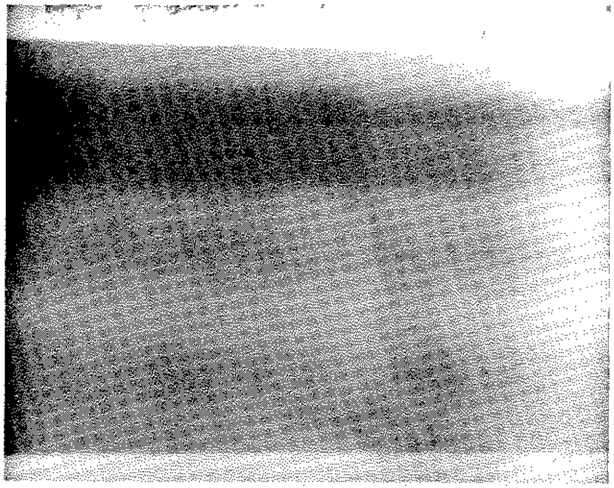
5c. Comparison of a pathline* (solid) and an instantaneous streamline (dashed) in oscillating plate flow.



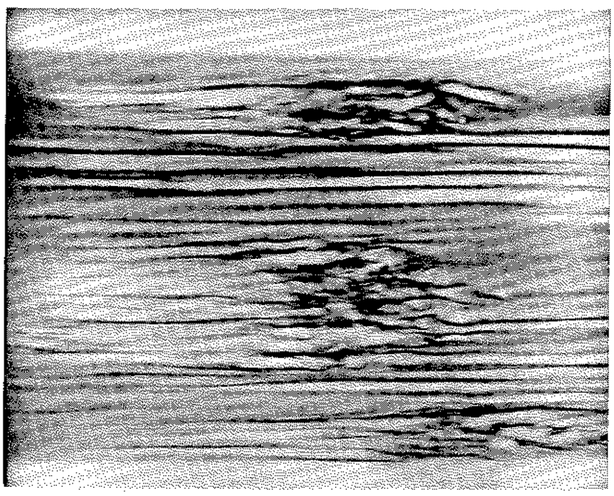
5d. Comparison of a streakline* (solid) and an instantaneous streamline (dashed) in oscillating plate flow.

**Defined on pages 3-4.*

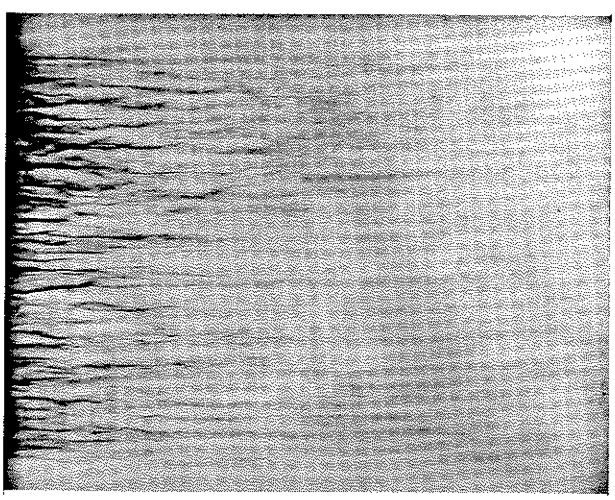
the flow pattern. For example, a slight increase in noise or roughness can cause a laminar flow to become turbulent. Such sensitivity to small changes



6a. Laminar flow in boundary layer shown by dye injection through a wall slit. The wall is in the plane of the paper.



6b. Turbulent spots in boundary-layer laminar-turbulent transition.



6c. Turbulent flow in boundary layer.

usually means that the theoretical equations cannot be solved with sufficient accuracy to predict the shifts in flow pattern, even if all the conditions affecting the flow were known with enough accuracy. It is then often expedient to determine the actual flow pattern for a given set of conditions using flow visualization.

Thus visualization can be of assistance for research, for direct solution of engineering problems, and for teaching.

Visualization has been used to provide significant information on such diverse flow phenomena as: waves in stratified fluids (FM-144, 145*), cells in rotating systems with thermal effects, flow in tee channels (FM-69), starting and stopping vortices (FM-10), supersonic and hypersonic wakes, start-up of compressible flow over sharp objects (FM-99), and flow models in turbulent boundary layers (FM-2).

A few examples where visualization has played a key part in solving scientific or engineering problems include subsonic diffuser flows (FM-49), boundary-layer interactions with shock waves (FM-27, 30), rotating stall in compressors (FM-7), wind-driven water waves (FM-148), vortex systems on wings of finite span (FM-24), flow models in transition to turbulence (FM-1), and magnus effect (FM-11). This list can be greatly extended by reading the titles of the loops in the NCFMF program.

II. Interpretation of Visual Images of Flow Patterns

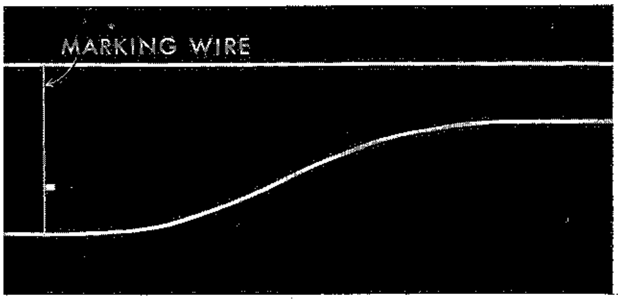
To use any visualization method (e.g., smoke lines, wall tufts, schlieren, birefringence, etc.) effectively, we must always ask ourselves: "What physical property of the flow or fluid does this picture show, and how do we interpret the patterns in the picture?" For instance, in any method involving the marking of fluid particles (e.g., smoke, dye, neutrally buoyant particles, hydrogen bubbles, surface powder), it is important to understand the relationships between the observed pictures and four concepts: pathlines, timelines, streaklines, and streamlines.

A *pathline* is the locus of points traversed by a given fluid particle during some specified time interval; the pathline is the particle's actual path during this interval.

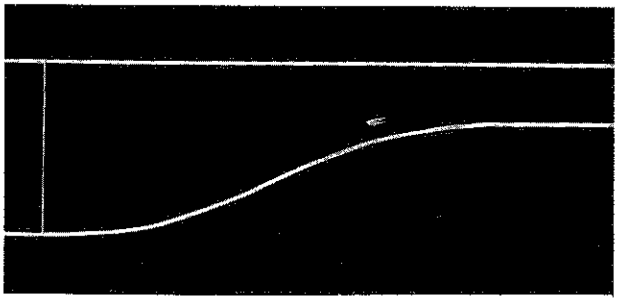
A *timeline* is a set of fluid particles that form a line at an instant in time. Thus we make a timeline visible by marking it with bubbles, by photo catalysis, or by other means, at a single instant. At later times both the shape and location of the timeline will generally have altered.

A *streakline* is the locus of particles which have

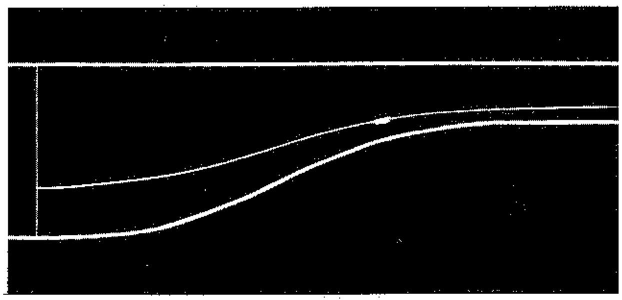
*FM numbers refer to film loops produced by the National Committee for Fluid Mechanics Films. They are available from Encyclopaedia Britannica Educational Corporation, 425 No. Michigan Avenue, Chicago, Illinois 60611.



7a. Water flow in a contracting channel. A small element is marked at time t_0 by hydrogen bubbles.



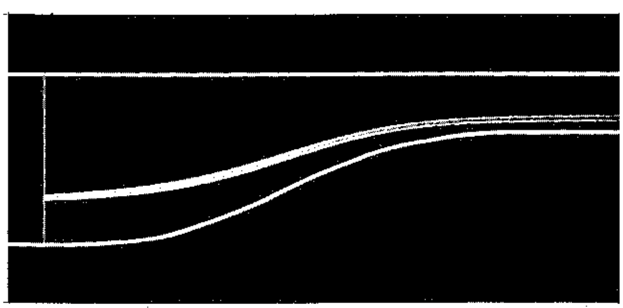
7b. Element at time $t_0 + 4.7$ secs.



7c. Element and superposed pathline.

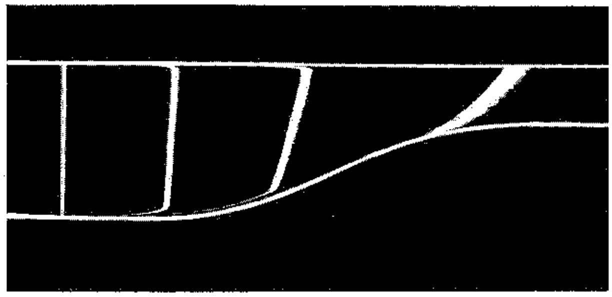
passed through a prescribed point during a specified time interval. Dye or smoke issuing slowly from a fixed injector shows the streakline passing through the injection point. In a steady flow new material points pass any given point continuously; the streakline for different time intervals will be composed of different particles, even in a steady flow.

A *streamline* is a line which at a given instant is everywhere tangent to the velocity vector. The streamline concept is essentially mathematical in nature. What we usually generate by visualization are streaklines, pathlines, or timelines. A field of streamlines and individual streamlines can be found in various ways from streaklines, pathlines, and timelines.

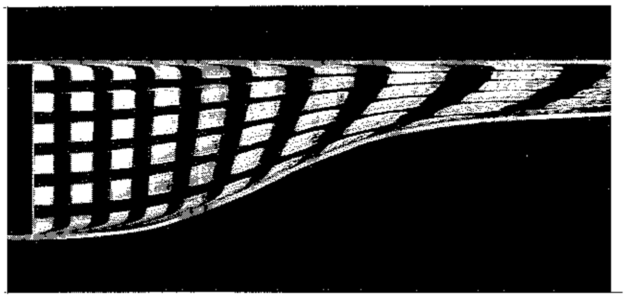


8. Streakline made visible by steady DC current on marking wire.

One way to make pathlines, streaklines, and timelines visible is the hydrogen bubble method, as illustrated in Figs. 7, 8, 9, and 10. (For more on the method see Section III.)



9. Narrow timelines marked by hydrogen bubbles.



10. Combined-time-streak markers (hydrogen bubbles).

In a steady flow, a streakline, pathline, and the streamline which all pass through a single point are identical. This follows from the fact that the velocity field is unchanging in time; hence each particle traverses the same trajectory. Thus each particle passing a fixed point in space follows the same streakline; this is its pathline (by definition), and is also everywhere tangent to the velocity vector field. Thus the streamline pattern is conveniently shown by a set of dye or smoke streaklines in steady motions.

In unsteady flows, the pathline, streakline, and streamline generally differ from each other, as seen in Figs. 5c and 5d. In unsteady flows the instananeous streamlines can be determined from a short time exposure or a multiple exposure, as in Figs. 5a and 5b. However, the procedure is a clumsy one.

Sometimes we want to determine the velocity vector field. In a steady, two-dimensional, incompressible flow, this can be done using either pathlines or streaklines alone since the flow is always parallel to them, and the velocity vector magnitude is inversely proportional to their separation. However, the numerical accuracy of such a method is not good, since we must measure small distances between lines that may not be very sharply defined.

If we use time and space markers simultaneously, we can extend the techniques to unsteady flows and also obtain more accuracy in steady flows. In the film this is called the "combined-time-streak marker," or "CTSM," method. An example of the CTSM method using moderate-sized squares as markers is shown in Fig. 10.

Using the CTSM method it is possible to obtain the velocity components in two directions, one of which must be the flow direction. One obtains a "section" through the flow. Measurements have been made in some cases where velocity components were obtained in two orthogonal planes at once. Similar results can be achieved in principle by photo-catalytic techniques. A great advantage of such techniques is that they provide measurements of instantaneous velocity profiles, although the accuracy is relatively low.

III. Techniques of Flow Visualization

Many kinds of flow visualization are known and have been employed in research, development, or teaching. Table 1 shows the more common methods grouped into five major types: (i) marker methods, (ii) optical methods, (iii) wall trace methods, (iv) birefringence, and (v) self-visible phenomena. Loops FM-21 and 22, Techniques of Visualization for Low-Speed Flows, illustrate some of the methods in Table 1.

The first column indicates whether the method is essentially a qualitative one or can be used to provide quantitative data on one or more variables of the flow field. In this regard, the opinions given are the author's. The second column suggests the normal range of application for each method.

References

1. **Prandtl, L. and Tietjens, O. G., *Fundamentals of Hydro and Aero Mechanics*, McGraw-Hill, 1934, Ch. V.**
2. **Clayton, B. R. and Massey, B. S., "Flow Visualization in Water: A Review of Techniques," J. Sci. Instrs. *44*, 1967, pp. 2-11: (includes modern bibliography).**
3. **Schraub, F. A., Kline, S. J., Henry, J., Runstadler, P. W., and Littell, A., "Use of Hydrogen Bubbles for Quantitative Determination of Time-Dependent Velocity Fields in Low-Speed Water Flows," Trans. ASME, Jou. Basic Eng. *87*, 1965, p. 429ff.**
4. **Symposium on Flow Visualization, ASME Symposium Volume, 1960, (includes extensive bibliographies).**

TABLE 1
Flow Visualization Techniques

Method	Measures	Fluid and Speed
MARKER METHODS		
Dye or smoke	Displacement; qualitative	Low-speed flows
Surface powder	Displacement; qualitative	Restricted to open surface liquid flow
Neutral density particles	Displacement; quantitative	Mainly liquids
Spark discharge	Displacement; qualitative	Limited to low density gases
Hydrogen bubble	Displacement; quantitative	Limited to electrolytic fluids
Aluminum flakes	Displacement, but orientation of flakes is shear-dependent; qualitative	Dense liquids
Photo-catalysis	Displacement; qualitative	
Electro-chemical luminescence	Velocity near surfaces; qualitative	Low speed, special solutions
OPTICAL METHODS		
Shadowgraph	$d^2\rho/dx^2$; quantitative	Hi-speed gases, or thermal or concentration gradients in liquids
Schlieren	$d\rho/dx$; quantitative	
Interferometer	ρ; quantitative	
WALL TRACE METHODS		
Tufts	Velocity direction; transition; separation; reattachment	No basic limit
Evaporative and chemical change at wall	Velocity direction; transition; separation; reattachment	No basic limit
BIREFRINGENCE	Shear stress; qualitative	Low-speed flows; special fluids only
SELF-VISIBLE		
Luminous	General motions; qualitative	Reacting or very high temperature
Phase interfaces	Displacements of interface	Two-phase fluids