

PHOTOGRAPHIC ANALYSIS OF FLUID FLOW

by

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The flow of gases, fluids and solids is a transient phenomenon which is extremely difficult to observe with the eye. If the eye is replaced with a lens and the rods and cones are replaced by a photosensitive material, such as photographic film or paper, a permanent record can be made. With the understanding of a few fundamental rules, a definite and excellent record can be obtained which then can be interpreted.

Before starting a study of flow patterns one must determine whether the phenomenon is in a steady or a transitory state. If the event occurring is in a steady state, still photography will suffice for recording it. If conditions are changing, sequence or motion pictures will fill the requirement. If the mechanical action (which, of course, includes the flow of liquids, gases and solids) is aperiodic, it becomes even more apparent that a photographic record is necessary. Obviously, the stroboscope is an ideal instrument for the visual observation of periodic events, but for erratic or discontinuous phenomena, the stroboscope alone is not sufficient for their examination.

Mechanical actions are defined as those which can be seen or recorded directly. Electrical actions are those phenomena which might be invisible or intangible, such as, pressures, sound, etc. The latter can be converted, through a transducer, into electrical energy which then can be seen as voltage changes on a cathode-ray oscilloscope or similar recording mediums. These definitions will become more important as the discussion proceeds to simultaneous recording of the flow patterns and pressures.

The time interval for an event to take place is the next factor to be considered.

A classical story exists concerning the study of the aerodynamic characteristics of a guided missile. Schlieren pictures were required of a scale model in a wind tunnel. The missile was to go from zero velocity to Mach 2.5 in a very short time. One engineer stated that one picture should be taken as the velocity became measurable and a second picture at Mach 2.5 when steady state was reached; that the passage of the missile through Mach 1 was so fast that there

would be no effect on the missile's behavior. A second engineer felt that a continuous record from 0 to 2.5 would be better for a complete analysis. A high-speed motion picture was made from Mach 0 to 2.5. As the missile passed through Mach 1, the violence of its passage was so great, it was apparent that the flight of the missile would be affected. The film record was such that a good analysis was possible and subsequent redesign produced a missile with better performance. But what it is important to note is that there is practically no event occurring which cannot be photographed.

The time of exposure is related to the field size and velocity. Especially is it important in the case of a single still picture that it be "crystal-clear sharp". For example, in photographing a moving object through two field widths, the first a 1-foot field and the second a 10-foot field, the apparent velocity will be ten times greater for the first than for the second. Therefore, the exposure time would have to be ten times as fast for the first in order to get a picture as sharp as the second one. It is true that the image size of the second will be but one-tenth the size of the first and that if it were enlarged to the same size as the first, the movement during equal exposures would be the same. The second picture actually seems sharper because of its reduced size. In observing Fig. 1, it is obvious that $BB_1 = 10 AA_1$, and in any unit time of exposure the object will move an equal distance on AA_1 and BB_1 .

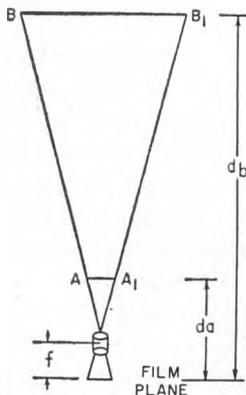


FIG. 1

The reduction factor is

$$R = \frac{d - f}{f}$$

where R is the number of times reduction

d is the distance from subject to film plane

f is the focal length of the lens in the same units as used in " d ".

If the subject was moving at 10 feet per second, the following table can be computed for various exposure times:

<i>Exposure time</i>	<i>Object movement during exposure</i>	<i>Object movement during exposure at 10 times reduction</i>
1 second	10 feet	1 foot
.1	1 foot	1.2 inches
.01	1.2 inches	.12 "
.001	.12 "	.012 "
.0001	.012 "	.0012 "
.00001	.0012 "	.00012 "
.000001	.00012 "	.000012 "

A sharp picture will be obtained if there is image movement of less than .001 inch. Therefore, for all practical purposes, an exposure time of .00001 second or 10 microseconds will make a sharp picture at one-to-one reduction while at ten-to-one reduction, 100 microseconds would be satisfactory. This same calculation is made for still, sequential and motion pictures.

There are times, however, in which pictures are obtained with a smeared image along the axis of movement. When measurements are to be made by comparing a sequence of two or more pictures, the leading edge of the smear should be used.

(In projecting motion pictures as such, the little bit of smear adds to the illusion of motion;—those motion pictures having very sharp pictures have a tendency to appear stroboscopic.)

The time magnification factor is important in determining picture-taking rates for sequential and motion pictures. In silent motion pictures, 160 frames or pictures are required for a 10-second sequence and 240 pictures are necessary for sound pictures. For frame-by-frame analysis, a smaller number of pictures may be required. Therefore, for projection,—we define

$$\frac{P_t}{P_p} = M$$

where P_t is the picture taking rate
 P_p is the picture projection rate
 M is the time magnification.

At 4800 pictures per second, the time magnification factor will be 300 times for silent projectors and 200 times for sound projection. For time-lapse pictures where 1 picture per second may be taken,

the time-magnification factor would be .0625 for silent pictures and .0417 for sound pictures.

As to field size, the width of the field will be inversely proportional to the focal length of the lens. Where explosions might take place, the longer focal length lenses offer greater protection for the equipment. For a rapid approximation for field width or distance from the lens to the subject for a given field width, the following formula, based on similar triangles, will prove useful:

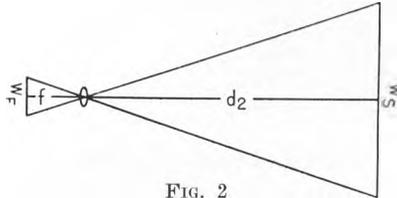


FIG. 2

$$\frac{W_f}{W_s} = \frac{f}{d'}$$

where W_f is the width of the film

W_s is the width of the field

f is the focal length of the lens

d' is the distance from the lens to the subject

Illumination of the subject plays an extremely important part in the study of flow patterns. In the case of liquids and gases, transmitted light is the basic method; while for the flow of solids, reflected light is generally used. To secure negatives of equal background density, the amount of transmitted light required will be about 1/40 that required for reflected-light pictures when using the camera lens at the same stop and the camera at the same picture-taking rate.

Practically there are but few basic lighting schemes for taking flow pictures;—though each engineer often modifies the over-all system to meet his own needs.

Specular light will give the best results from the standpoint of the flow patterns in clear liquids and gases. The specular light is light travelling in straight lines—preferably originating from a point source.

Diffuse light is scattered light and is best illustrated by light coming from a frosted lamp or from opal glass. The light can, or may, enter the clear glass in a straight line, but as it strikes the diffusing surface, it is broken up and no longer travels in the same direction as it entered, as is shown in Fig. 3.

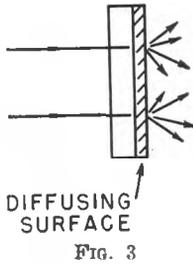


FIG. 3

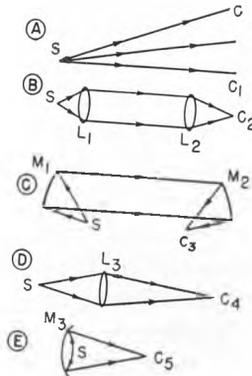


FIG. 4

There are various methods used for producing optical systems furnishing specular or quasi-specular light. The more specular the light, the sharper the flow pattern. Good observation of the flow pattern depends on the variation of the index of refraction in the medium due to pressure and/or temperature changes. Since these lines of differences may be very small and sharply delineated, the straighter the path of the light, the better.

In Fig. 4, the basic systems are illustrated. In A, a point source S is placed at some distance from the camera lens which is at C_1 . If the subject is placed between the points S and C_1 but nearer C_1 and the lens focused on the plane of subject, a shadowgraph picture will be obtained. Such a shadowgraph will show the flow patterns in gases and transparent liquids, as well as dispersion of solids in liquids and the phenomena of solution and mixing.

Light sources which are generally used for this purpose are:

1. Ribbon-filament incandescent lamps
2. High pressure mercury-vapor lamps*
3. Zirconium arc lamps
4. Spark
5. Electronic flash

In B and C lenses or mirrors are placed so that L_1 and M_1 will form a collimated beam of light and then L_2 and M_2 will re-image the source at C_2 and C_3 . The subject is placed in the collimated beam, and the camera lens focused upon the subject. (A reference for this basic optical system will be indicated in the discussion of schlieren photography.)

Simplified systems are shown in D and E. D employs a single condensing lens. A large diameter lens is usually used so that the

* For any picture taking rate above 16 per second, d-c should be used.

background density is produced uniformly over the negative. The subject is usually placed between the condensing lens and the camera lens. (Two typical condensing lenses could be the 12" f.l. 6" diameter and the 21" f.l. 14" diameter.) When the lens is replaced by a mirror, as in E, the subject is placed between the lamp and the camera lens. Field size will determine the diameter of the mirror to be used.

From these basic systems, there will be slight deviations for shadowgraph and schlieren photography. In both shadowgraph and schlieren, the differences in the index of refraction within the medium are recorded. The shadowgraph pictures will show gross changes in index which would be produced and could be photographed by one of the five basic specular optical systems. If a stop is placed in the focal plane of the subject or at the principal focus of the lens, a schlieren picture is produced which shows even minute differences in the index. The stop can be either a knife edge or an iris diaphragm at the principal focus of the lens.

The schlieren system can be modified to produce color schlieren by introducing a continuous spectrum at the plane of the filament or slit. A second slit can be added at the plane of the spectrum to produce a narrow band of the color spectrum.

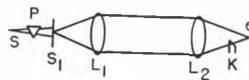


FIG. 5

Figure 5 shows the schematic employing the "B" system of Fig. 4, but with the 60° prism (P) interposed between S and S₁; S₁ is the adjustable slit and K the knife edge at the principle focus of the lens.

The diffuse light source or optical system is used both for transmitted and reflected light subjects. These systems are easier to set up than the specular systems. Typical ones are shown in Fig. 6.

A diffuse lighting system was used for the photography of the effect of missiles entering water with both still cameras and high-speed motion-picture cameras. The tank used for this purpose is about 4 feet high. The back of the tank toward the lights is opal glass so that an evenly diffused surface is obtained. Photo-flood lamps are used to back-light the tank. The camera is placed in such a position that the impact point, the splash and the trajectory of the missile through the water can be photographed. The sche-

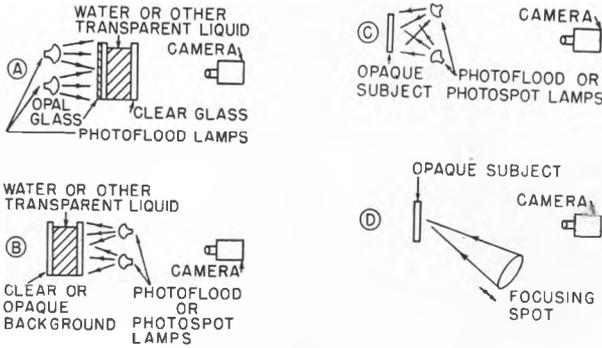


FIG. 6.

matic setup is shown in Fig. 6(a). The missile was photographed in silhouette. See Fig. 9.

Front lighting is generally used for the photography of liquid and gaseous flow and for the study of cavitation and bubble formation,—though occasionally front- and back-lighting will produce better pictures. The front-lighting setup is shown in Fig. 6(b), and some examples in Fig. 10.

Where opaque subjects are being photographed, for example, the flow of solids, Fig. 6(c) and (d) illustrate the basic methods. Figure 6(d) is especially applicable to the photography of small areas. In the case that mirror surfaces are encountered, the light must be brought in on the optical axis of the lens, but most surfaces are rough enough to permit the lights to be used at an angle. No matter how fine the scratches are, the light will be broken up so that the subject can be identified. For the flow of solids, time-lapse photography may be resorted to, where the picture-taking frequency may be 1 per hour, per day or per week. A typical example of this would be silver migration through phenol plastic.

In some cases, light sources themselves are photographed. Neon and argon glow lamps can be used effectively to study intake velocities and patterns into chambers. In the succeeding part of this paper describing how specific liquid studies are made, the effect of flow may or may not be present. Furthermore, many of the techniques described are applicable to gas studies.

The pattern of the flow of a liquid into a partitioned chamber could not be seen because of the all metal construction of the housing. A board (black) was made up with a number of neon lamps mounted on it. One side of the lamp terminals was wired in parallel and the other side of the individual lamps connected to selected positions in the chamber. With the chamber as shown in

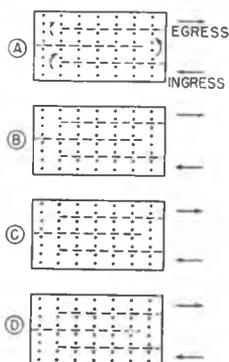


FIG. 7

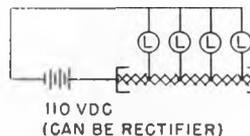


FIG. 8

Fig. 7(a) and the lamps mounted so that the partitioned chamber was clearly outlined, the water would close the circuit on the affected lamps as it rushed into the chamber. The schematic of the circuit used is shown in Fig. 8. A motion-picture camera taking 16 pictures per second photographed the progressive action. In Fig. 7(b) the water flow has started and two air pockets are noted. In 7(c), other pockets have developed and some eliminated, while in 7(d) the water has started to flow from the egress. These films were analyzed in a film reader, picture-by-picture. Master sheets were prepared prior to the reading for easy transcription. From the data obtained, the water position could be plotted against elapsed time.

Cavitation studies have always presented many problems from the standpoint of ship's hull and propeller design. In working on this project, a number of different techniques have been employed. In cavitation, high-speed motion pictures, high-speed still pictures and high-speed sequence have been used extensively.

Cavitation and the presence of gas bubbles in liquids or vapor in air require similar treatment. Schlieren photography has been used as well as shadowgraphy the best to portray these phenomena. The ebullition of air in a propeller wake and the formation of vapor trails by aircraft are typical of these reactions.

One of the finest examples of this type of work has been done by Werner Kraus of the Bayer Chemical Works in Germany. He employed color schlieren to study mixing and stirring processes. He used an a-c arc lamp as a source with a prism for creating the spectrum. The schlieren slit was placed at the principal focus of the objective lens. The mirror scheme shown in Fig. 3(c) was applied. This method is known as the Loepler process and was pushed to its present valuable state by Dr. Hubert Schardin. He

used both still cameras and motion-picture cameras to get his pictures. In a note from him, he points out that they were interested in qualitative results only, but that J. G. Van de Vesse, T. H. Delft, Netherlands, has been using this method for quantitative measurements.

The Naval Ordnance Laboratory, at Silver Spring, Maryland, has been using the method shown in Fig. 6(a) for studying the cavitation formed by missiles falling into water and other liquids. The missiles are of different shapes and enter the water at varying velocities. The rotating prism high speed cameras were used to photograph these events.

The David Taylor Model Basin has been studying propeller and hull design in towing tanks and water tunnels. High-speed micro-flash (electronic flash) is used to get the tip action where the cavitation action begins. High-speed motion pictures are made of comparatively narrow fields (up to five feet) and normal-speed motion pictures are made of the gross effects on the full run through the towing tank. High-speed motion pictures and micro-flash pictures are made by looking through windows into the water tunnel.

One word of caution with respect to looking into windows;— plastic windows will cause more trouble than glass. A barium crown or "Aquaplate" glass can best be used for windows. This glass is clear and not tinted green as is ordinary plate glass. The external surface (air side) should be coated by the fluoride, if possible. Condensation can also be very troublesome and a double window with a dehydrating agent such as silica gel helps in overcoming this problem.

As one is using a camera looking into water, the focusing scale is modified because of the difference in index of refraction between air and water. The scale distance is multiplied by a factor of .75. If the fixed focus on a camera is normally 24 feet in air, the fixed focus becomes 18 feet in water.

One window should be kept clear for the camera and other ports used for the lights. The ports for the lights should be kept as near as possible to the optical axis of the lens. Highly concentrated spots are desirable for penetrating the water. Among these lamps are:

- (a) PH750R
- (b) 300 watt
- (c) #4560 Airplane landing lamp
- (d) General Radio "Microflash" unit

The California Institute of Technology has used the Edgerton electronic-flash unit up to 20,000 flashes per second for cavitation studies. In order to secure the high rate, several power supplies were used in tandem. A continuously moving film was used and hence with a synchronizer on the camera, ribbon-like pictures were obtained.

Other typical problems which have been extensively studied are:

The Waterways Experiment Station at Vicksburg, Tenn., has been making motion studies of water flow by normal- and high-speed photography. The flow of water over dams and levees, through tunnels and through water courses, such as the Mississippi River Basin model, are recorded.

Dr. Paul Fye, now of the Naval Ordnance Laboratory and formerly of Woods Hole Oceanographic Institute, has been photographing under-water explosions. In the earlier pictures, high-

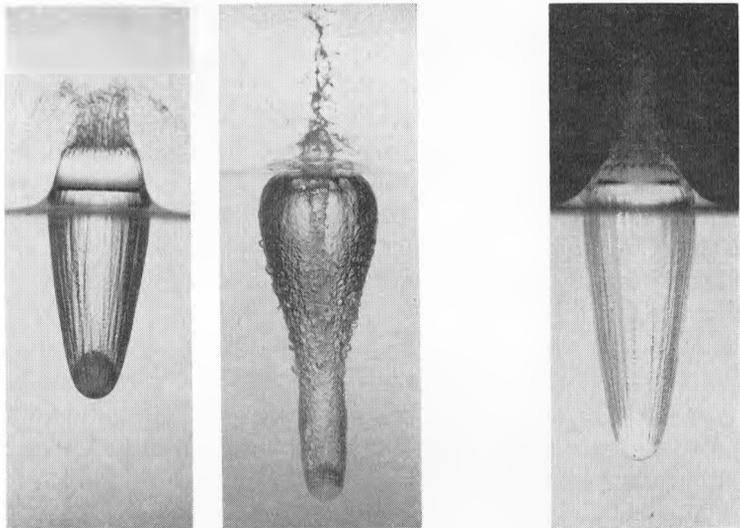


FIG. 9. AIR-WATER ENTRY OF A SPHERE, COURTESY OF NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

speed rotating-prism cameras were lowered in water-tight bells to where the test discharge was to take place. Jigged onto the bell was the explosive and also photoflash lamps. The sequence of operation was as follows:

1. The camera was started.
2. When the camera was at full speed, the photoflash lamp (G.E. #50 or equivalent) was ignited.

3. As the photoflash lamp was approaching its peak, the charge was fired.
4. The camera was stopped with a limiting switch when "the fireworks were over."

A weighted white sheet was generally suspended beyond the charge to get better contrast.

(Note: By means of a high-speed oscillographic camera placed on board the ship and connected to a transducer, simultaneous recordings of pressure and the mechanical effects of the explosion could be made. In order to validate the readings, zero time should be placed on both camera films. The zero time could be initiated from another pair of contacts on the firing switch. A 1,000-cycle oscillator with sufficient power to drive two neon or argon lamps ($\frac{1}{4}$ watt) would furnish "the pips" for timing. When a camera is kept in the dark, the timing lights may not fire. In order to overcome this, a 28-volt d-c bias which is on all of the time will permit the lamps to fire when the 1,000-cycle "pips" come through the circuit.)

Fye later submerged a modified Bowen-Knapp camera to 12,000 feet to secure a sequential series of underwater explosions.

With a continuous camera, the film will be running in a vertical plane or along the "Y" axis. Therefore, the input to the cathode-ray oscilloscope will be on the "X" axis only. (On older oscilloscopes, the tube was rotated 90° and the high gain "Y" amplifier was used. Newer scopes have equal gain "X" and "Y" amplifiers.) A P11 coating on the scope tube with good accelerating voltage will give good records.

The effects of water currents on the ocean bed have been studied by Dr. Ewing and later Dr. Harold Edgerton. Ewing used an incandescent source and Edgerton has been using both incandescent and electronic flash. Rubicoff has been working off southern France with incandescent lights and electronic flash. Edgerton has been working at depths up to 16,000 feet and there are plans to go even deeper.

In 1943, the question arose as to what happened to a torpedo when it became entangled in a net. As an exploratory test, a series of high-speed motion pictures was made at Silver Springs, Florida, in daylight. At that time only Eastman Super XX film was available. At depths down to 10 feet, utilizing the white sandy bottom as a reflector, full exposures were obtained at 1,000 pictures per second with a rotating-prism camera. A fair exposure was obtained at 4,000 pictures per second. With the fast films available today, 4,000 pictures per second can be obtained in sunlight.

Later Chesterman of the Royal Naval Scientific Service made



FIG. 10. CAVITATION PHOTOGRAPHY BY ELECTRONIC FLASH, COURTESY OF THE ORDNANCE RESEARCH LABORATORY, STATE COLLEGE, PENNSYLVANIA

beautiful pictures of propeller cavitation and torpedo ejection from the submarine's torpedo tube. These same types of pictures have been made by the United States Navy.

At the Morris Dam installation, the Navy has been studying the effect of impact of torpedoes as they strike the water. The velocities of the torpedo in air would correspond to that of a destroyer- or aircraft-launched torpedo. Motion pictures, both normal- and high-speed, document the event.

The photographic-instrumentation field is expanding rapidly. Cameras are being designed to occupy minimum space and yet be extremely rugged. Auxiliary equipment is being designed to work with the cameras effectively and efficiently. New light sources are being developed. Films are being made that have greater speed and finer grain. Color films are coming onto the market which may equal the speed of black-and-white film. New film bases are being developed which will allow operation of equipment at 65°F.

There is one criticism to be offered, however. The present equipment that is available for the actual analysis of the films is the weakest link of the chain in all these studies.

Motion pictures can be observed qualitatively by projecting them in a standard projector. One manufacturer has placed a hand crank and a frame counter on the projector which permits the observer to advance the pictures one-by-one. They, however, did not calibrate the focal length of the lens. With the tolerances of manufacture of the lenses, $\pm 4\%$ error can be introduced unless there is a scale in the original picture. This lens should be replaced by a calibrated photographic objective—not a projection lens.

For frame-by-frame analysis, film readers are available but these are sometimes awkward to use. The magnification factor may be some odd number such as 17 or 23 times. These readers were designed primarily for microfilm transcription.

One instrument company has designed a 10-times magnification reader for 16mm film. Movable cross-hairs for vertical and horizontal measurements are read on direct reading dials to the nearest .001 inch. The film is observed on a translucent screen.

There is a gap from these to the very elaborate laboratory units which cost from \$15,000 upward.

In conclusion, photography is playing a very important role in the recording of the transient events that occur in fluid flow. As is indicated by the papers that are presented before the hydraulics

conferences, many phases of photography are used to illustrate practically every paper.

It will be to everyone's advantage to contact various manufacturers with his problems. This allows the manufacturer to design equipment which is built for the task at hand and not "jury-rigged". The future needs are not modification of existing equipment, but engineering requirements for design.