# HANDBOOK OF *High-Speed* PHOTOGRAPHY

GENERAL RADIO COMPANY WEST CONCORD, MASSACHUSETTS

GENERAL RADIO COMPANY

*WEST CONCORD, MASSACHUSETTS*

NEW YORK • PHILADELPHIA • SYRACUSE • WASHINGTON
CLEVELAND • CHICAGO • DALLAS • ORLANDO
LOS ANGELES • SAN FRANCISCO • TORONTO • MONTREAL

GENERAL RADIO COMPANY (OVERSEAS)

ZURICH, SWITZERLAND

REPRESENTATIVES IN PRINCIPAL COUNTRIES

# HANDBOOK OF *High-Speed* PHOTOGRAPHY

## on the cover

Did you ever wonder what the first drop of milk *really* looks like when it splashes on the bottom of your glass? If you could open and shut your eyes in an interval of three millionths of a second (at precisely the right instant), you would see the sombrero-shaped object pictured on the cover. Since your eyes won't function this rapidly, the next-best approach is to synchronize a stroboscope to flash at the proper instant — and an exciting new world of high-speed activity is revealed for the first time.

To illuminate the milk drop, the General Radio Type 1531-A Strobotac® electronic stroboscope was triggered electrically by a light-sensitive photocell. The falling droplet interrupted a small beam of light directed at the photocell, and the resulting change in light intensity produced the trigger pulse. An adjustable time delay was inserted in the trigger circuit with General Radio's new Type 1531-P2 Flash Delay so that the flash could be timed to occur precisely at the instant the milk drop landed.

Total exposure time, with the Strobotac set on HIGH INTENSITY, was about three millionths of a second. The original image on Royal Pan film was enlarged approximately ten times to obtain the cover presentation. For more milk-drop photographs, turn to page 28.

GENERAL RADIO COMPANY
WEST CONCORD · MASSACHUSETTS · USA



FORM 3100-A

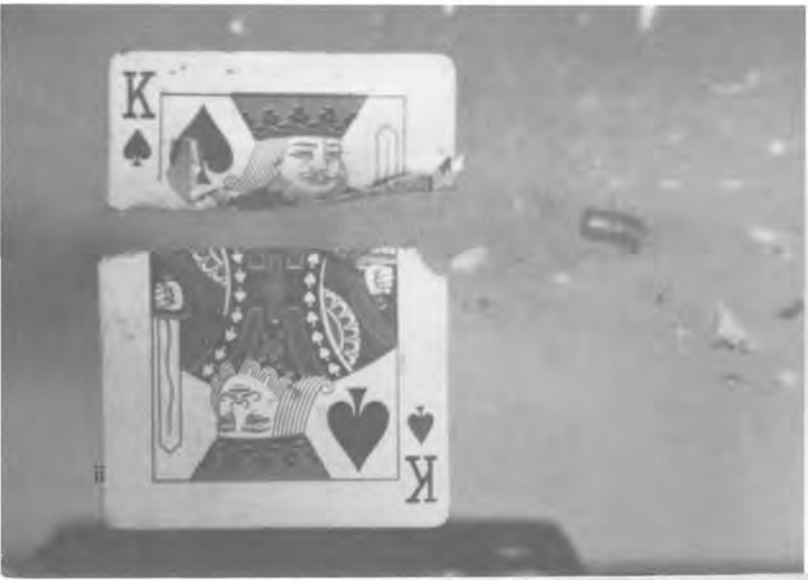
Printed in U.S.A.

# TABLE OF CONTENTS



A playing card being split by a .22-calibre rifle bullet traveling at approximately 1150 feet per second. Note how the slug has tipped and started to tumble from contact with the card.

This action was photographed with a single high-intensity flash from the type 1531-A Strobotac® electronic stroboscope. The reflector was removed, and the flash lamp was located about 14 inches from the subject. To trigger the flash, a microphone was placed forward of the rifle muzzle and connected to the Strobotac through a small voltage amplifier. The camera lens (135-mm Schneider, with a Kodak PORTRA +3 close-up attachment) was set at f/8 and located about 10 inches from the card. (Polaroid Type 47 film, 3-microsecond exposure.)



# TABLE OF CONTENTS (continued)



# ACKNOWLEDGMENT

Many people collaborated on the preparation of this handbook. The text was written by William E. O'Neel during his summer employment in the Marketing Research Department at General Radio Company while he was a student at the Harvard Graduate School of Business Administration. Technical data, methods, and photographs were contributed by William R. Thurston, Marketing Research Manager; Michael J. Fitzmorris, Development Engineer; and Rudolph F. Recke, Photographer, all of General Radio Company. Dr. Harold E. Edgerton, of M.I.T., the father of electronic-flash photography, furnished a number of the photographs, lent his advice and counsel, and graciously consented to write the Foreword. Many other individuals, institutions, and industrial firms contributed photographs and data. To all of these, our sincere thanks.

— The Editors

# FOREWORD

When I first heard about high-speed photography only a few, perhaps a dozen, were fortunate enough to use the technique. The main use was in the study of ballistics and shock waves. All of this work followed directly from the splendid research of Mach more than one hundred years ago. He used spark gaps to produce light from a small volume to expose silhouette photographs of bullets and shock waves directly onto hand-made glass plates.

The day has now arrived when high-speed photography as a research tool is commonplace. This book is to introduce high-speed photography to the masses. Not only will the elaborate research laboratories of our day use the method but almost everyone will. It is symbolic that high-school students today are doing involved experimental research that would have been considered very difficult only a few years ago. The tempo of our time is fulfilled. The new generation arises with skills and techniques that those of the older generation did not, or could not, exploit.

The perfection of the new xenon FX-6A flash lamp by Kenneth Germeshausen and his collaborators, among whom I consider it a joy to be included, has aided in bringing the new Strobotac® electronic stroboscope to a form and performance where increased use is obtained. A paralleling development of the circuits and packaging by Michael Fitzmorris and Malcolm Holtje of General Radio Company, together with the cooperation of many of the staff of that company, has resulted in the unique instrument whose use for photography is described in detail in the following pages.

Developments in photography have contributed to the use of the Strobotac as a practical device for high-speed photography. Of special interest is the Polaroid-Land photography system which permits the almost immediate inspection of the end result. Then another picture can be taken at once to correct a fault or to improve the photography. Not only the Polaroid system but photography in general with its many aspects can be used in many ways with the flashes of light from the Strobotac.

The advent of this book, then, marks a new era which brings the high-speed photographic system of experimental research into the reach of everyone. I forsee great results when we can "see" and "understand" the many now mysterious and unknown things that whir and buzz about us.

I look forward to the second edition of this book which will, no doubt, contain many outstanding examples contributed by those of you who now read this edition. So get busy and do send in examples for us to enjoy.

Harold E. Edgerton

# INTRODUCTION

As interest and activity in the study of high-speed phenomena become more prevalent, the use of related photographic techniques is rapidly increasing in importance. Many persons engaged in high-speed studies lack the services of an experienced photographer; consequently, they often experience unnecessary difficulty in applying photographic techniques to their observation or measurement problems. Similarly, professional photographers assisting in work of this nature often spend considerable time either searching through reference materials or making costly trial exposures to gather the specific information they require.

This handbook is designed to assist both the general experimenter and the professional photographer in their use of General Radio equipment to study high-speed phenomena. While not exhaustive, it summarizes the most useful ideas and techniques in a single reference source, and the bibliography lists many excellent sources of more detailed or specialized information. Operating characteristics of the General Radio Type 1531-A Strobotac® electronic stroboscope, the Type 1531-P2 Flash Delay, the Type 1536-A Photoelectric Pickoff, and the Type 1532-D Strobolume are included, and several typical applications are described to illustrate the solution of problems commonly encountered in high-speed photography.


Figure 1.
The STROBOTAC®
electronic stroboscope —
versatile light source
for both high-speed
photography and visual
stroboscopy.

section 1

# Type 1531-A Strobotac® electronic stroboscope

## 1.1 GENERAL DESCRIPTION.

The Type 1531-A Strobotac® electronic stroboscope is a versatile, inexpensive, high-speed light source designed to fill a wide variety of both photographic and non-photographic needs in science and industry. Its light weight and compact design make it extremely convenient to use, and its light output is suitable for taking many different types of photographs. (See Section 1.2.) A self-contained electronic oscillator enables the unit to operate independently at flash rates from 110 to 25,000 flashes per minute. The flash rate is continuously variable throughout this range, and it can be accurately set (±1%) by means of the large calibrated dial on the instrument panel.

The Strobotac is housed in a unique carrying case, which doubles as an adjustable stand. (See Figure 1.) The cover is permanently attached to prevent misplacement or damage to the instrument while in transit, and the unit is fully portable to any location where the required power is available. Either 120 or 240 volts ac, 50- to 60- or 400-cycle power is satisfactory; maximum input power is 35 watts.

Photographers particularly appreciate the ease with which the lamp reflector can be positioned. The long-throw light beam can be rotated through 360° horizontally and 180° vertically without movement of the instrument case, and the reflector can be quickly and easily removed from the flash-lamp mount when it is desired to illuminate hard-to-reach areas.

## 1.2 LIGHT OUTPUT CHARACTERISTICS.

In high-speed photography, the greatest advantage of the Strobotac is its ability to deliver high-intensity light flashes of extremely short time duration. Flashes less than 1 microsecond (1 millionth of a second) long can be obtained at the highest flash-rate setting, and the longest flashes are only 3 microseconds in duration (measured between one-third-peak-intensity points).

With such short light flashes, the photographer can achieve high photographic resolution of rapidly moving objects. For example, a point on the periphery of a wheel two feet in diameter spinning at 3600 rpm moves about 4.5 inches in 1/1000 of a second, a movement too great for the ordinary mechanical shutter to "stop." Even a conventional electronic flash unit with a 40-microsecond flash would produce a blurred picture, because a peripheral point moves almost 0.2 inch in that time. But the 1-microsecond light flash produces an exposure with less than 0.005-inch movement of the wheel's circumference, adequate resolution for most observations and measurements. (See also Figure 10, page 17.)

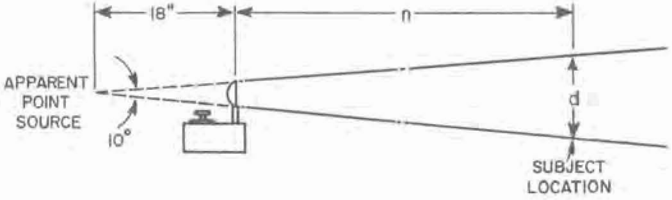
When the reflector is in place, the light output is concentrated into a long-throw 10° beam (measured at one-half-peak-intensity points) with an apparent source 18 inches behind the reflector front. Outside this 10° cone the light intensity falls off sharply, so that the area of reasonably constant illumination is not large. Since a variation of 2:1 in incident light intensity corresponds to an exposure increment of approximately one f-stop setting, the diameter of the 10° beam cone provides a good approximation to the useful illumination area of the Strobotac when the reflector is attached. These spot diameters are tabulated for several lamp-subject distances in Table 1. If this beam diameter is too small to light the subject adequately, remove the reflector and notice how a larger surface area can be illuminated by the bare flash lamp. The light density falling on a given subject area decreases when this is done, but, with care, useful exposures can often be obtained. Section 5 mentions several techniques for improving marginal exposure conditions, and when these are employed a single Strobotac will usually illuminate satisfactorily an area six to eight feet wide.

The Strobotron spark discharge gap, when viewed from one end, closely approximates a point light source. Because of this, the light output can be concentrated optically into a high-intensity beam for special applications, and it is extremely useful in shadowgraph photography. This technique is used principally for the study of violent fluid disturbances, such as the shock waves created by a rifle bullet. Details of the methodology are given in Section 5.3.

The small size and accessibility of the flash lamp make the Strobotac ideal for many specialized applications. In microphotography, for example, the unit provides ample light for photographing objects or organisms under high magnification, yet the flash duty cycle is low enough to prevent destruction of delicate subjects due to overheating. Fiber optics can be easily employed with the Strobotac to provide a small, intense light source some distance from the unit itself.

## TABLE 1

Illuminated Spot Diameters




| Lamp-to-Subject Distance (n) | Diameter of Illuminated Spot At Half-Peak Intensity Points |
|---|---|
| 1 feet | 5 inches |
| 2 | 7 |
| 3 | 9 |
| 4 | 12 |
| 5 | 14 |
| 6 | 16 |
| 7 | 18 |
| 8 | 20 |
| 9 | 22 |
| 10 | 24 |

When the Strobotac is flashing continually, the total light intensity of each flash varies with the flash repetition rate. Approximate values of total light output are tabulated in Table 2 for the operating limits of each range-switch setting, and these values can be used as a rough guide for the conversion of exposure data obtained at one flash rate into exposure guides for photographing the same subject at different flash repetition rates. They will prove of little value, however, in determining initial exposure settings, owing to the widely varying conditions prevailing among different subjects and the consequent difficulty of converting light-intensity data into exposure settings. The guide numbers provided in Table 5 (page 20) are recommended for this purpose.

Figure 2 shows the output light-intensity waveshape for a Strobotac flash. Light output rises smoothly and rapidly, then drops sharply to less than 15 percent of peak value. This results in a highly efficient, short-duration flash, since the lingering low-intensity afterglow,

## TABLE 2

Light Output Data
Type 1531-A Strobotac electronic stroboscope

| Speed-Range Switch Setting | Flashes Per Minute | Bare Lamp Peak Candle-power* | Peak Beam Intensity (Million Beam Candlepower) | Flash Duration Measured At 1/3 Peak Intensity (microseconds) | Total Light Output (BCPS)** |
|---|---|---|---|---|---|
| RPM (high) | 25,000<br>4,000 | 4,200<br>11,000 | 0.21<br>0.55 | 0.8 | 0.17<br>0.44 |
| RPM (med) | 4,200<br>600 | 24,000<br>44,000 | 1.2<br>2.2 | 1.2 | 1.4<br>2.6 |
| RPM (low) | 700<br>100 | 85,000<br>140,000 | 4.2<br>7.0 | 3.0 | 13<br>21 |
| 60∼ Line | 3,600 | 30,000 | 1.5 | 1.6 | 2.4 |
| EXT INPUT | | | | | |
| Low Intensity | Single | 11,000 | 0.55 | 0.8 | 0.44 |
| Med Intensity | Single | 44,000 | 2.2 | 1.2 | 2.6 |
| High Intensity | Single | 140,000 | 7.0 | 3.0 | 21 |

*Measured two feet from bare lamp with arc perpendicular to phototube-lamp line.
**Beam candlepower seconds.

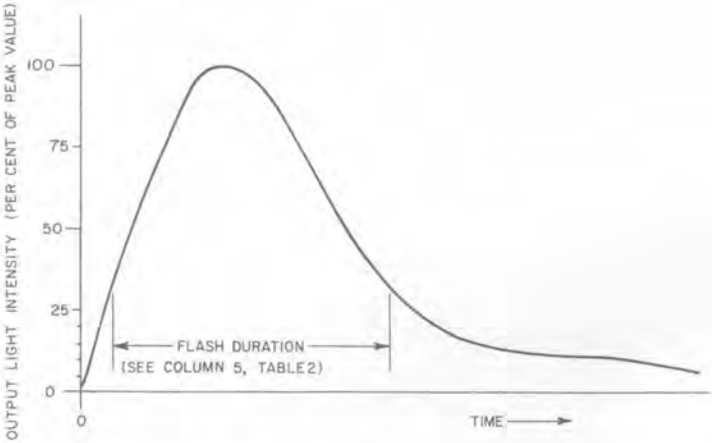



Figure 2. Output light intensity waveform of the Type 1531-A Strobotac electronic stroboscope.

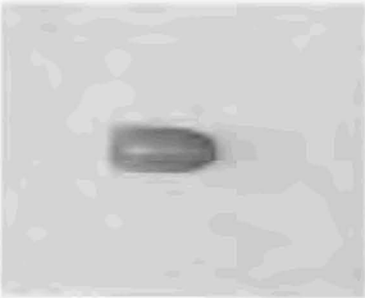


Figure 3. A .22-calibre rifle bullet photographed in flight. The faint gray streak extending in front of the bullet along its path is exposure resulting from flash-lamp afterglow. A single, high-intensity flash of the Strobotac was triggered with a microphone to stop the projectile's 1100-feet-per-second velocity. (Polaroid Type 47 film, ASA 3000, 3-microsecond exposure at f/22. The reflector was removed from the lamp.)

or flash "tail", contains only a small fraction of the total energy radiated. (See Figure 3.)

## 1.3 SYNCHRONIZATION.

Probably the most difficult problem facing the high-speed photographer is the task of synchronizing the strobe-light flashes with his subject's motion so as to expose his film at the desired times. If the flash is either too early or too late, the subject will be "stopped" in the wrong position, and in many cases the resulting photograph will be useless.

Synchronization becomes even more important under conditions of high ambient light intensity, because fast shutter speeds must then be used to prevent blurring of the moving object. Not only must the strobe fire in proper synchronism with the moving subject; the camera shutter must also be synchronized to be fully open at the instant the flash occurs.

These problems can be overcome in most instances by careful planning of the synchronization techniques to be used. However, considerable ingenuity is required to cope successfully with the peculiar requirements of some special-purpose applications.

1.3.1 EXTERNAL TRIGGERING AND INTERNAL DELAY CHARACTERISTICS. The Strobotac can be triggered by a wide variety of externally provided signals when the range switch is set on any of the EXTERNAL INPUT positions. An electrical signal of at least 6 volts peak-to-peak amplitude can be used, but a simple contact "make" or "break" is also satisfactory. Before connecting a trigger signal to the INPUT jack, be sure the range switch is not in an EXT INPUT position so the thyratron tube won't "hold over".[1] As soon as the plug is inserted, the range switch may be positioned where desired.

It is important to set the RPM dial correctly when triggering the Strobotac externally, since this control varies the sensitivity of the instrument to electrical input signals, and low-amplitude pulses will not trigger a light flash if the RPM control is improperly set. With some triggering methods, the RPM dial can also be used to insert a variable time delay between the trigger signal and the light flash, and care must be taken to assure that the proper amount of delay is achieved for the purpose intended.

With the RPM dial rotated fully clockwise, the Strobotac triggers with either a positive-going electrical signal or by the opening of a set of contacts connected to the INPUT jack. In either case, the light flash follows the trigger signal with only a few microseconds delay. In practically all instances this small delay introduces no difficulties, and the light flash can be considered instantaneous.

As the dial is rotated counterclockwise from this position, a point will be reached where the Strobotac flashes once without being externally triggered. Approximately 90° rotation is usually required to reach this "flash point", but it varies somewhat from instrument to instrument. If the dial is rotated back clockwise to a position just before the flash point (usually 10 to 15 degrees), the maximum sensitivity to positive external trigger pulses will be obtained. No appreciable change in the instrument's flash-delay characteristic is effected over this range of settings.

When the RPM dial is set at any position counterclockwise of the flash point, the trigger characteristics of the Strobotac are considerably altered. At these settings the unit can be flashed only with a negative electrical signal, or by the closing of a set of external contacts. However, there is a time delay between the trigger pulse or contact closure and the Strobotron flash. The amount of this delay varies according to the setting of the RPM dial. If the dial is fully counterclockwise, the flash is delayed approximately 20 milliseconds (thousands of a second). This time lapse increases as the dial is rotated back clockwise, and it may reach as high as 300 milliseconds (3/10 second) at a point just counterclockwise of the flash point. If a negative trigger pulse is used that is of shorter time duration than the maximum internal delay of about 200 milliseconds, the light flash will be triggered by the trailing edge, or positive-going slope, of the pulse.

---

[1] See Section 3.6 of the instruction manual for the Type 1531-A Strobotac electronic stroboscope, General Radio Form 1531-0100.

These flash-delay characteristics are summarized in Figure 4 for quick reference. The measurements on which this diagram is based were separated by several seconds, so they simulate single-flash synchronization. These data are not valid for high-repetition-rate, multiple-flash synchronization with RPM dial settings counterclockwise of the flash point, and all values given are approximate and may vary from instrument to instrument.

The internal delay characteristic of the Type 1531-A Strobotac should be kept in mind in the planning of synchronization systems, because it can sometimes be used in lieu of a special delay device. This method of obtaining a time delay, however, may introduce appreciable time jitter; for this reason, use of the Flash Delay is preferred.

1.3.2 MINIMUM-DELAY TRIGGERING WITH A NEGATIVE PULSE OR CONTACT CLOSURE. If a negative pulse or contact closure is available for triggering, and the delay shown in Figure 4 cannot be tolerated, slight modifications must be made in the triggering connection. For triggering on the leading edge of a negative electrical pulse, a General Radio Transformer Cable, Type 1532-P2B, should be used to reverse its polarity. The oversize plug on one end of this cable is plugged into

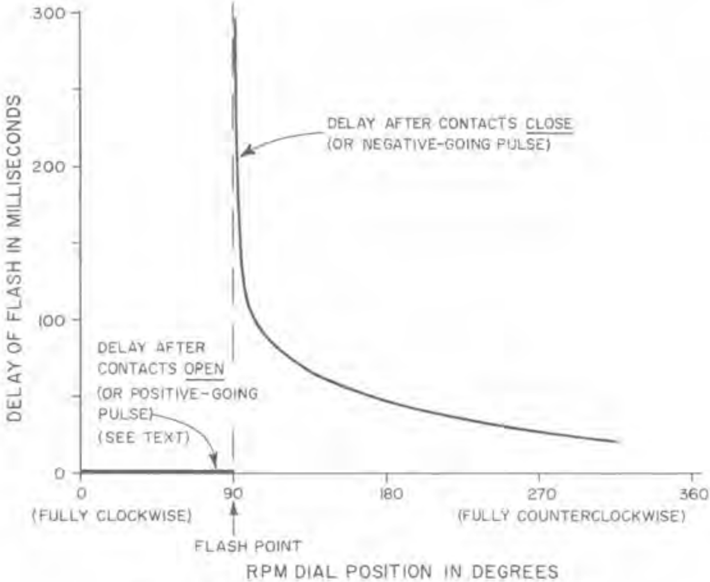
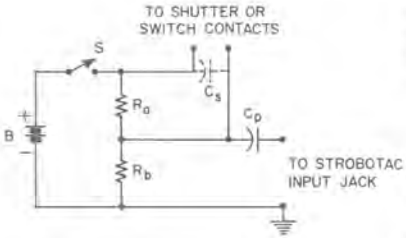



Figure 4. Internal delay characteristics of the Type 1531-A Strobotac electronic stroboscope.




B - 12-volt (or greater) battery
$R_a$, $R_b$ - 1-megohm, ½-watt carbon resistors
S - SPST ON-OFF switch
$C_s$ - Optional capacitor to prevent multiple triggering from contact bounce. Start with about 0.01 $\mu$f (100 v, dc) and increase capacitance until only one flash is triggered from each contact closure.
$C_p$ - 0.01 $\mu$f, 100-volt capacitor

NOTE: Set RPM dial fully clockwise.

**Figure 5. Circuit for triggering the Strobotac by a contact closure with minimum time delay.**

the Strobotac INPUT jack, and the normal phone plug on the other end is connected to the pulse source in the usual manner. The RPM dial is then adjusted for positive-pulse triggering. (See Section 1.3.1.) Practically any pulse transformer can be connected to perform the same function.

A contact closure can be made to trigger the Strobotac with minimum delay by the simple inverting circuit diagrammed in Figure 5. The necessary parts can be purchased at any radio or electronics parts supply house for less than $2.00, and only a few minutes are required to assemble them. Contacts in camera shutters equipped for "X" synchronization normally operate satisfactorily with this circuit, but some difficulty may be experienced if the contacts "bounce" when closing. (The Strobotron will fire each time electrical contact is made.) A small capacitor (approximately 0.01 microfarad) connected across the contact terminals usually solves this problem.

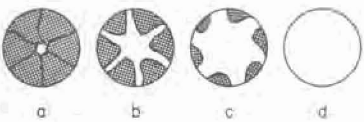
The Type 1531-P2 Flash Delay contains special circuitry to provide the pulse-inverting function described above, so with this unit minimum delay triggering can be accomplished directly from a contact closure. See Section 2.5 for details.

1.3.3 CHECKING SHUTTER FLASH SYNCHRONIZATION. Whenever shutter flash contacts are used to trigger the Strobotac, synchronization should be carefully checked before the film is loaded into the camera. To do this, open the lens diaphragm to its widest aperture, remove the back of the camera to expose the rear of the lens, aim the camera at the Strobotac reflector, and trip the shutter. When the Strobotac flashes, a bright, clear circle of light should be visible through the camera lens. If the light circle appears no brighter than when the Strobotac is disconnected, the flash is not properly synchronized. A small light circle, or a circle with a jagged edge, indicates that the light flash is occurring during either the opening or closing of the shutter blades. (See Figure 6.)

The camera used should have "X" synchronization, necessary with most types of electronic flash illumination.

The camera should not be loaded with film until consistent synchronization is observed, because normal variations in shutter speed and flash contact operation may cause erratic results if the light flash occurs too close to the shutter opening or closing. Uneven exposure will result if the shutter blades are only partially open during the light flash, and the film will be completely dark if the flash occurs either too early or too late.

Figure 6.
Patterns seen through the camera lens when proper shutter flash synchronization is being checked.




In views a, b, and c, the shutter blades are either opening or closing, and the flash delay should be adjusted until a clear, bright circle of light is observed, as in view d.
The camera must be directed at the Strobotac reflector, and the light circle must be considerably brighter than when the Strobotac is disconnected.

1.3.4 SYNCHRONIZATION OF MULTIPLE LIGHT SOURCES. Frequently it is desirable to flash two or more Strobotac electronic stroboscopes in synchronism, either simultaneously or separated by known time intervals. For simultaneous triggering, all instruments can be simply connected to the same trigger signal, or the OUTPUT TRIGGER of one can be connected to the INPUT of a second through the Type 1532-P2B Transformer Cable, as shown in Figure 7. The OUTPUT TRIGGER of the second unit can be connected to the INPUT of a third in a similar fashion, etc. Notice that the oversize plug on the cable must be inserted in the INPUT jack of the slave unit for proper operation.

In order to flash a series of Strobotac electronic stroboscopes sequentially from a single trigger event, varying amounts of time delay must be inserted in their INPUT circuits. The Type 1531-P2 Flash Delay is ideal for this purpose, but almost any time-delay circuit would be suitable. If the Type 1531-P2 Flash Delay is used, be sure to use the Type 1531-0461 Adaptor Plug, furnished with the instrument, to connect the two-conductor plug on the Type 1532-P2B Transformer Cable to the three-conductor Flash Delay INPUT jack. DO NOT attempt to achieve the same result by plugging the Type 1532-P2B plug only part of the way into the Flash Delay INPUT jack, because both the Transformer Cable and the Flash Delay may be damaged if the plug is accidentally fully inserted.

With either of the above setups, the RPM dials of the Strobotac electronic stroboscopes should be positioned clockwise of the flash point. (See Section 1.3.1.) Within this region, a very fine timing adjustment can be made by a slight change in the RPM dial position. The flash of a particular unit can be made to occur slightly later by a clockwise motion of the dial and slightly earlier by a counterclockwise motion AS LONG AS THE DIAL REMAINS CLOCKWISE OF THE FLASH POINT. In this fashion multiple units can be synchronized within tolerances of much less than a microsecond.

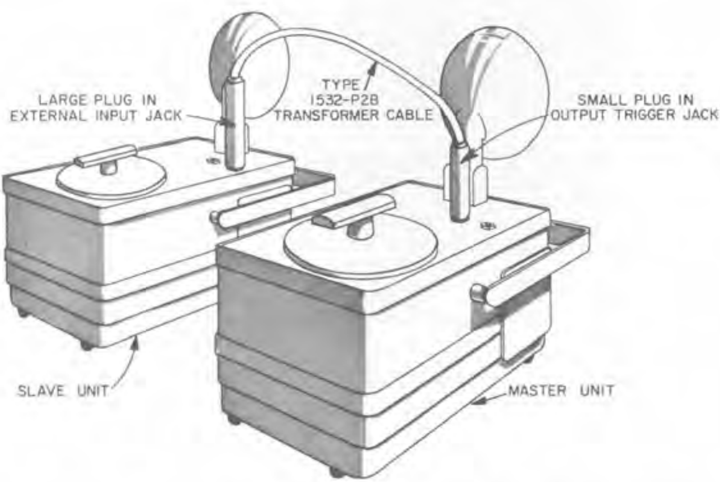



Figure 7. Use of the Type 1532-P2B Transformer Cable in connecting multiple Strobotac units for synchronized flashing.

# Type 1531-P2 Flash Delay and Type 1536-A Photoelectric Pickoff

## 2.1 GENERAL DESCRIPTION.

The Type 1531-P2 Flash Delay is an accessory designed to be used when the Type 1531-A Strobotac® electronic stroboscope is triggered externally. Its primary purpose is to insert a controlled amount of time delay between trigger pulses and the resulting Strobotac light flashes. It functions from either single pulses or pulse trains with any repetition rate usable by the Strobotac. With the Strobotac range switch set on EXT INPUT, LOW INTENSITY, repetition rates of 600 to 800 flashes per second can be reliably achieved, and flash rates as high as

Figure 8a. The Type 1531-P2 Flash Delay and the Type 1536-A Photoelectric Pickoff shown ready for use with the Type 1531-A Strobotac electronic stroboscope.

1000 per second are sometimes possible, depending on the condition of the Strobotron flash lamp. The Strobotac range switch must be set on one of the EXT INPUT positions when used with the Flash Delay.

The Type 1536-A Photoelectric Pickoff is used with the Type 1531-P2 Flash Delay to trigger the Strobotac in synchronism with moving objects. A small lamp, a light-sensitive photocell, and a lens mounted in the end of the Pickoff convert abrupt changes in the reflectivity of a moving surface into electrical impulses. These signals are then amplified by the Flash Delay and fed to the Strobotac INPUT jack. The Flash Delay and Pickoff are shown connected ready for operation with the Strobotac in Figure 8a.

To obtain the most reliable and consistent triggering from the Photoelectric Pickoff, a sharp discontinuity in reflectivity should be used as a trigger point on the subject. Small markers made from Scotch brand Silver Polyester Film Tape No. 850 or reflective metallic foil make ideal trigger marks, and on dark surfaces white or silver paint is sometimes satisfactory. Generous quantities of both a dull black and a shiny reflective tape are supplied with the instrument for this purpose.

Probably the most common application for the Flash Delay and Photoelectric Pickoff is in the observation and photographing of the various phases of high-speed repetitive phenomena. When the Strobotac has been synchronized with the subject's motion (e.g., the rotation of an electric fan's blade), its motion is "stopped" so it appears to be stationary. Then as time delay is inserted into the triggering circuit, the subject is illuminated at a slightly later time on each cycle, and thus appears to "slip" forward in position (e.g., if the fan is actually rotating clockwise, it will appear to "turn" clockwise slowly as the time delay is increased by the rotation of the DELAY knob clockwise).

## 2.2 TIME-DELAY RANGES AND ADJUSTMENT.

The RANGE switch on the panel of the Flash Delay has five positions. In the extreme counterclockwise position power is disconnected, and the unit is inoperative.

When this switch is in position 1, 2, or 3, the time-delay range provided is as follows:

Range 1 100 microseconds to 10 milliseconds
Range 2 1 millisecond to 100 milliseconds
Range 3 10 milliseconds to 1 second

Time delay is continuously variable within each of these ranges and increases approximately linearly as the DELAY control is rotated clockwise. Start with Range 1 and work to Ranges 2 and 3 if more delay is needed.

The EXT position is used to trigger the Flash Delay from contact points. (See Section 2.5.)

## 2.3 MULTIPLE/SINGLE-FLASH TOGGLE SWITCH, SINGLE-FLASH PHOTOGRAPHS.

When this switch is in the MULT position, a delayed light flash occurs for each trigger pulse applied to the Flash Delay INPUT jack. The amount of delay can be conveniently adjusted to illuminate the subject in the desired portion of its cycle.

If the toggle is switched to the SINGLE FLASH position, the train of delayed trigger pulses being fed to the Strobotac is interrupted, and the light flashes cease. A single flash can then be obtained by closure of a set of contacts (such as camera-shutter flash-synchronization contacts) connected to the small jack mounted near the Flash Delay power cord. This light flash follows the next trigger pulse received at the unit by the preset amount of time delay, so the subject is illuminated in the same phase of its cycle that was visually observed when the switch was in the MULT position. This capability greatly facilitates the single-flash photography of moving objects in positions of particular interest.

When preparing for single-flash pictures, first set the toggle switch to MULT position and adjust the Pickoff for proper operation. Adjust the DELAY control until subject appears "stopped" in position for the desired picture. Then switch toggle to SINGLE FLASH and set the Strobotac range switch to the desired intensity. The shutter speed must be slow enough so the shutter is open for at least one complete cycle of the moving object. When the camera shutter is tripped, the Strobotac will flash once at the preset point in the subject's cycle.

An auxiliary switch and cable can be used if available cameras are not equipped with "X" synchronization. In this case the shutter must be opened on "Bulb," the Strobotac flashed by closure of the switch, and then the shutter closed.

## 2.4 TRIGGER-PULSE REQUIREMENTS.

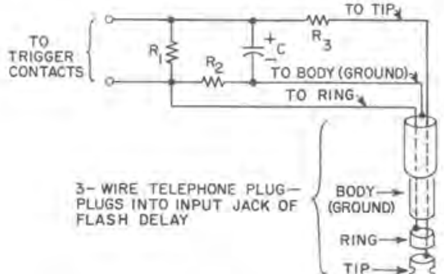
The Flash Delay can be operated directly from the Photoelectric Pickoff through connection to the Flash Delay INPUT jack. However, other signal sources may also be used in lieu of the Photoelectric

Pickoff, provided that they deliver positive pulses of at least 0.3-volt amplitude to the Flash Delay. A standard two-wire telephone plug can be used to make the connection, with the Type 1531-0461 Adaptor Plug furnished with each unit. Use of the adaptor avoids confusion and prevents instrument damage when connecting electrical trigger signals to the Flash Delay. When the adaptor is in place, ordinary two-conductor plugs can be used in the trigger circuit wiring. It may be left plugged in for extended periods of time to insure against accidental insertion of a two-conductor plug directly into the INPUT jack.

## 2.5 TRIGGERING FROM EXTERNAL CONTACTS.

There are two ways the Strobotac may be triggered through the Flash Delay with a simple contact closure. If minimum time delay is desired between a contact closure and the light flash, the contacts are connected to the jack near the Flash Delay power cord and the RANGE switch is set to EXT. The Strobotac RPM dial is then set just clockwise of the flash point for maximum sensitivity. (See Section 1.3.1.) Camera shutters equipped with "X" flash synchronization contacts can be used in this manner to trigger the Strobotac directly. If the Flash Delay were not used, the light flash would follow the contact closure by at least 20 milliseconds. (See Figure 4.)

An alternative method permits the full range of delay to be utilized while the stroboscope is triggered from a contact closure. The circuit shown in Figure 8b, which can be readily constructed from parts available in any radio supply store, is simply plugged into the Flash Delay INPUT and the trigger contacts are then connected to this circuit, as indicated. This method can be used with the shutter contacts on cam-




$R_1$ = 33 kilohms, ½-watt carbon resistor
$R_2$ = 33 kilohms, ½-watt carbon resistor
$R_3$ = 33 kilohms, ½-watt carbon resistor
C = 5 $\mu f$ (50 v, dc) electrolytic capacitor (note proper polarity)

Figure 8b. Contact-delay circuit, for triggering the Flash Delay by a contact closure with full range of time delay available.

## TABLE 3

Time Delay Required in Trigger Circuit
for Various Shutter Synchronization Settings

| Shutter Synchronization Setting | Approximate Time Delay Between Contact Closure And Full Shutter Opening |
|---|---|
| "X" | Negligible |
| "F" | 5-6 milliseconds |
| "M" | 20 milliseconds |

eras that delay the shutter opening intentionally after the built-in contacts close to allow sufficient time for flash bulbs to reach peak light output. (The delays provided by common flash-synchronization settings are listed in Table 3.) Since the Strobotac delivers its peak light intensity immediately upon triggering, the built-in camera delay at "F" and "M" flash settings causes the Strobotron lamp to fire before the shutter is fully opened. Consequently, an appropriate amount of delay must be inserted in the external trigger circuit if a camera equipped only with these synchronization settings is to be used. A delay of approximately 5 milliseconds, for example, should be inserted in the triggering circuit of most inexpensive universal-focus cameras, as these cameras are usually equipped for "F"-type synchronization.

The appropriate delay time for the shutter being used should be roughly set into the Flash Delay by means of the DELAY control. Then, while visually checking the shutter-flash synchronization, as outlined in Section 1.3.3, make a fine adjustment. Again, consistent synchronization should be observed before film is loaded into the camera.

# Type 1532-D Strobolume

## 3.1 GENERAL DESCRIPTION.

The Type 1532-D Strobolume is a high-intensity light source capable of delivering up to 15 times the total light output of the Type 1531-A Strobotac® electronic stroboscope. Unlike the Strobotac, the Strobolume is not a true stroboscope, because it contains no internal oscillator for repetitive flashing at fixed rates. A switch is provided for single-flash operation, but either contacts or an electrical signal is required for multiple-flash triggering.

a. Front view.

b. Rear view.

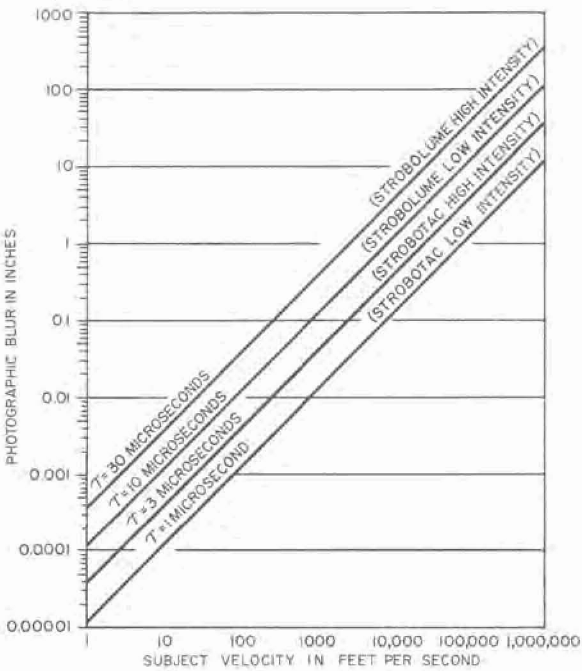
c. View showing lamp assembly removed from case.

Figure 9. Type 1532-D Strobolume.

The Strobolume is primarily useful in photography when a large area must be illuminated or extremely high brightness is required. Its lamp assembly may be removed from the instrument case for easy access to the subject (see Figure 9C), and a threaded socket is provided so the assembly may be mounted on a photographic tripod if desired.

## 3.2 LIGHT OUTPUT CHARACTERISTICS.

Light output data for both of the Strobolume operating modes are tabulated in Table 4. Notice that the flash duration for high-intensity operation is more than 30 times the shortest flash duration obtainable from the Type 1531-A Strobotac. This greater flash time increases the photographic blur of a moving object for any given subject velocity, and so the increased illumination is not achieved without a sacrifice. The relationship between subject velocity and photographic blur for typical flash durations of both the Strobotac and the Strobolume is graphed for easy reference in Figure 10. This diagram should be




where $\tau$ = flash duration

Photographic blur = 0.000012 x subject velocity x $\tau$.

Figure 10. Photographic blur *vs* velocity and exposure time.

**TABLE 4**

Light Output Data
Type 1532-D Strobolume

| | Maximum Flashes Per Minute | | Peak Beam Intensity (Beam Candlepower, Continuous Operation) | Approximate Flash Duration (microseconds) | Total Light Output (BCPS) |
|---|---|---|---|---|---|
| | Continuous | Intermittent | | | |
| LOW INTENSITY | 3000 | 3000 | 140,000 | 10 | 1.4 |
| HIGH INTENSITY | 60 | 1200 | 10,000,000 | 30 | 300 |

consulted when there is any question about the maximum flash duration that can be tolerated.

### 3.3 TRIGGERING.

Either external contacts or a high-voltage electrical signal may be used to trigger the Type 1532-D Strobolume, but contacts usually are preferred. Contacts connected to the CONTACTOR jack on the rear of the instrument with a standard two-conductor phone plug cause a light flash upon closing, not upon opening.

It is possible to trigger the Strobolume with a positive electrical pulse applied to the CONTACTOR jack, but the pulse must be at least 200 volts in amplitude and more than 20 microseconds long to function reliably with all instruments.

A variety of special requirements can be satisfied by the triggering of the Strobolume directly from the Strobotac. For this purpose the Type 1532-P3 Trigger Cable connects between the Strobotac OUTPUT TRIGGER and the Strobolume CONTACTOR jack. Up to 20 microseconds may elapse between the Strobotac flash and the beginning of the Strobolume flash with this arrangement, so a multiple exposure may result if the Strobotac reflector is directed toward the subject. Care must be taken not to exceed the maximum flash rates and operating times specified in the Strobolume instruction manual (Sections 2.3, 2.4).

section 4

# Exposure Data

When exposed to the extremely bright, short-duration light flashes common in high-speed photography, photographic emulsions do not have constant sensitivity for different exposure times. Because of this phenomenon, called "reciprocity-law failure," the effective film exposure is not directly proportional to the product of light intensity and exposure time. Film sensitivity characteristics at these extremely short exposure times vary widely between film types, and the standard exposure index ratings used by manufacturers cannot be used reliably to estimate lens aperture settings.

Several of the more popular, higher-speed films recommended for use with the Strobotac are listed in Table 5 along with suggested guide numbers for each flash intensity setting. Notice that the guide number must be divided by the lamp-subject distance in feet plus 1.5, because the Strobotac beam produces the same effective illumination as if it emanated from a point source approximately 18" behind the front of the reflector. Effective lens apertures calculated in this manner should be considered first approximations to the best actual camera settings, and trial exposures will often be necessary to optimize for the particular reflectivity and contrast characteristics of the subject being photographed.

The recommended photographic guide number for HIGH intensity operation of the Type 1532-D Strobolume is 25 with film rated at ASA 100. This number should be divided by the lamp-subject distance in feet to obtain a preliminary f/number setting.

At extremely short camera-subject distances, the camera lens must be moved away from the film plane in order to bring the subject into focus. This decreases the amount of light reaching the film, and the lens aperture setting must be adjusted to compensate for this loss. The curve in Figure 11 provides a straightforward means for determining the amount of adjustment required for either a given bellows extension or a given image magnification.

The Strobotac produces good results with orthochromatic as well as panchromatic black-and-white films, because a large part of the light energy emitted by its flash falls in the blue-green region where both types of film are sensitive. (See Figure 12 for a graphical comparison of film sensitivities to the spectral content of a xenon flash tube emission.) Orthochromatic films, however, will not take full advantage of the unit's output, and panchromatic types may be preferable for applications where the flash intensity is marginal.

The equivalent color temperature of the Strobotac flash is approximately 6500°-7000° Kelvin. (See also Figure 12.) While the bare flash may produce acceptable results with color films under some conditions, use of the filters recommended in Table 5 will result in improved color balance.

Occasionally, in the photographing of subjects moving at extremely high speed, the exposure created by the lingering flash "tail" (see Figure 3) will cause a slight blur ahead of a moving object's image in the direction of its travel. This undesirable effect can be reduced with black-and-white film by the reduction of the lens aperture and a corresponding increase in the negative development time. Exposure during the higher intensity period of the light flash is thus emphasized, and the effective flash duration is reduced. In other words, contrast is improved by "underexposing and overdeveloping." High-speed films usually work best for this purpose because of their greater sensitivity to the lower total exposure.

**TABLE 5**

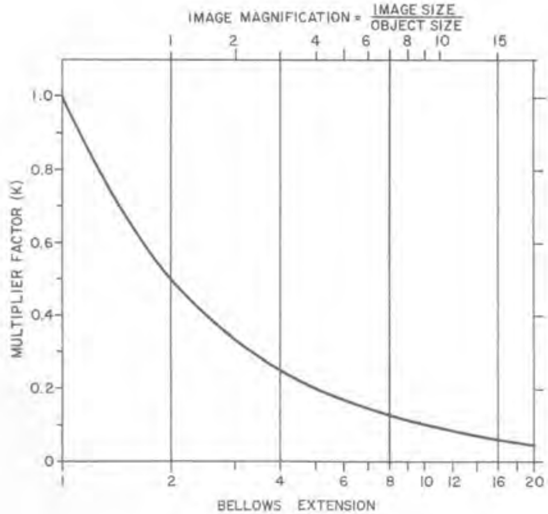
Recommended Guide Numbers for Type 1531-A Strobotac electronic stroboscope

| Film Type | ASA Speed Index | Guide Number: Low Intensity (High RPM) | Guide Number: Medium Intensity (Medium RPM) | Guide Number: High Intensity (Low RPM) |
|---|---|---|---|---|
| Polaroid Types 42 and 52 | 200 | * | 15 | 22 |
| Polaroid Type 44 | 400 | * | * | 30 |
| Polaroid Type 47 | 3000 | 15 | 45 | 80 |
| Eastman Tri-X | 200 | 15 | 30 | 75 |
| Eastman Royal X Pan | 1600 | 27 | 62 | 150 |
| Eastman Ektachrome E-3 (Daylight) CC40Y Filter | 50 | * | * | 8 |
| Eastman High Speed Ektachrome (EH-135) (Daylight) with CC40Y Filter | 160 | * | * | 14 |
| Super Anscochrome (Daylight) with CC20Y Filter | 100 | * | * | 13 |

*Not recommended.

$$\text{Effective lens aperture (f/number)} = \frac{\text{guide number}}{1.5 + \text{lamp-subject distance in feet}}$$

When camera is placed extremely close to the subject, this computed f/number setting should be multiplied by the K-factor found from Figure 11 to find the recommended lens setting.




Indicated aperture = K $\times$ effective aperture

$$\text{Bellows extension} = 25.4 \times \frac{\text{Lens-to-film plane distance in inches}}{\text{Focal length of camera lens in millimeters}}$$

Figure 11. Multiplier factor for determining indicated aperture (correct lens f/number setting) from effective aperture (calculated from guide number data) when camera is located close to the subject.

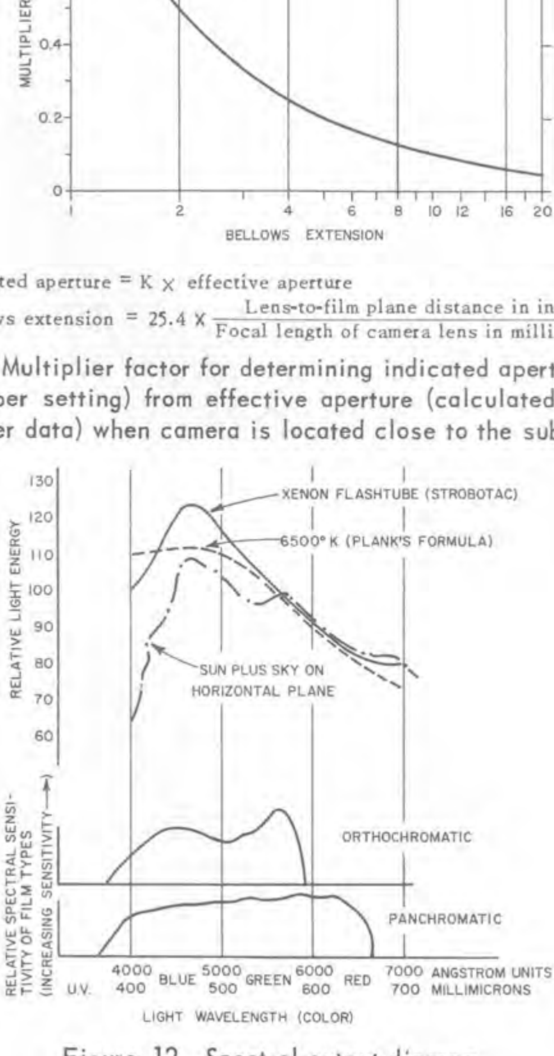



Figure 12. Spectral-output diagram.

TABLE 6. Summary of Characteristics of Several Commercially Available Light Sources for High-Speed Photography

| Light Source | Duration μsec | Max Repetition Frequency flashes/sec | Peak Light Intensity million beam cp | Lamp Voltage volts | Lamp Input Energy per Flash watt-sec | Time Delay | Photographic Exposure Data |
|---|---|---|---|---|---|---|---|
| GR Type 1531-A Strobotac electronic stroboscope | 0.8 to 3.0 | 800 - 1000, depending on tube | 0.2 to 7 | 800 | 0.008 to 0.25 | Internal: uncalibrated, 20-300 msec<br>External: 100 μsec to 1 sec, uncalibrated, with Type 1531-P2 Flash Delay | see Table 5 |
| GR Type 1532-D Strobolume | 10 / 30 | 50 continuous / 20 in bursts of up to 7 sec | 0.14 / 10 | 2500 | 0.8 / 2 | external only | Guide No. 25 for ASA 100 film |
| E G & G Models 515, 6, 7 Xenon Flash Illuminator Assembly | 150 | 0.2 | 1.3 | 900 | 100 | external only | n.a. |
| E G & G Model 549 Microflash | 0.5 | 0.2 | 50 | 18,000 | 8 | adjustable, uncalibrated 3 - 1000 μsec | For 2-ft lamp-subject distance: Panatonic-X-f/8, High-Speed Ektachrome-f/5.6 with CC50Y filter |
| E G & G Type 2307 Double Flash Light Source | 0.3 | equivalent to 10,000 - 2,000,000 in bursts of two flashes | n.a. | 7000 | 0.12 | between flashes - calibrated 0.5 - 100 μsec (accuracy - ±0.5 μsec) | For silhouette photography only (insufficient light for reflected-light photography) |
| E G & G Model 502 Multiple Micro-flash Unit | 1 | 25 - 100,000 in bursts of up to 20 flashes | 0.2 | 10,000 | 1.5 | between flashes-adjustable 10 μsec to 40 msec | n.a. |
| E G & G Type 501 High-Speed Stroboscope | 1.2 / 2.1 | 6000 in bursts of up to 0.8 sec / 800 in bursts of up to 1.5 sec | 0.13 candlepower with FX - 3 tube / 0.4 candlepower with FX - 3 tube | 8000 | 0.3 / 1.3 | external only | n.a. / For high-speed panchromatic film and parabolic reflector on lamp, guide number is 5 - 10 |

section 5

# Lighting Techniques

## 5.1 GENERAL.

Many times objects to be photographed at high speed do not naturally contrast well with their backgrounds, and it is difficult to achieve clear, high-definition pictures of them. Often this situation can be greatly improved simply by either a light or a dark background behind the immediate subject. If several objects or moving parts are being studied simultaneously, different colors or shades of paint can be used to improve contrast between them.

Light colored backgrounds, such as white paper or cardboard, tend to produce troublesome reflections when the light source and camera are directed at the subject from certain angles. Relocation of the Strobotac may help in these situations, or it may be desirable to switch to a dark, non-reflective backdrop (black velvet is about the best, but any dull black surface may be used). If bright "hot spots" are evident, the Strobotac should be moved farther away from the subject or the light beam should be bounced onto the subject from a light-colored, diffusing reflector (white matte paper is a good material for this purpose).

Side reflectors can be used to advantage when one side of the subject is brightly illuminated and another side is darker. Household aluminum foil is a good material for this as it is easy to work with and has good reflectivity. It will diffuse light effectively if it is loosely crumpled, then gently opened out and formed into a rough reflector surface.

Scotchlite is another reflecting material which has many uses in high-speed photography. It is manufactured and sold by Minnesota Mining and Manufacturing Company and has the peculiar characteristic of reflecting light striking its surface back in the direction from which it came, with an efficiency almost 200 times that of an ordinary white surface. Scotchlite is available in widths up to 36", packaged in rolls from 5 to 72 yards long. It has a pressure-sensitive adhesive backing for easy application to flat surfaces. The silver (#3270) and imperial white (#3280) colors are most highly reflective, and consequently most useful for photographic purposes.[1]

Because of its extremely high reflective efficiency, Scotchlite is an ideal material for marking critical portions of a moving object being studied at high speed. A small Scotchlite marker will contrast well with its background even under high ambient light conditions, and the relative position of these markers can often be discerned in a photograph that would otherwise be useless.

## 5.2 AUXILIARY REFLECTORS FOR STROBOTRON FLASH LAMP.

When it is necessary to remove the Strobotac reflector in order to illuminate hard-to-reach spots, the drop in light concentration often is a problem. Ordinary household aluminum foil, when carefully smoothed on a flat surface and attached to one side of the flash lamp with clear cement, serves as an effective miniature reflector to minimize this reduction. Be sure the flash lamp is clean and the brightest side of the foil is placed toward the inside of the lamp. Best results are usually obtained when the foil covers about half of the lamp between the two spark electrodes, as shown in Figure 13.

Alternatively, the flash lamp may be chemically silvered by the Brashear[2] process to produce a highly reflecting surface on its exterior.

---

[1]For further information on the use of Scotchlite, see William G. Hyzer, "Engineering and Scientific High-Speed Photography," The Macmillan Company, New York, New York, 1962, pp 324-325.

[2]See J. Strong, "Procedures in Experimental Physics," Prentice-Hall, Inc., New York, 1943, pp 152-157.

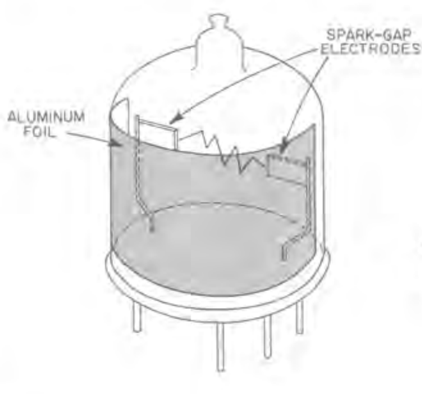


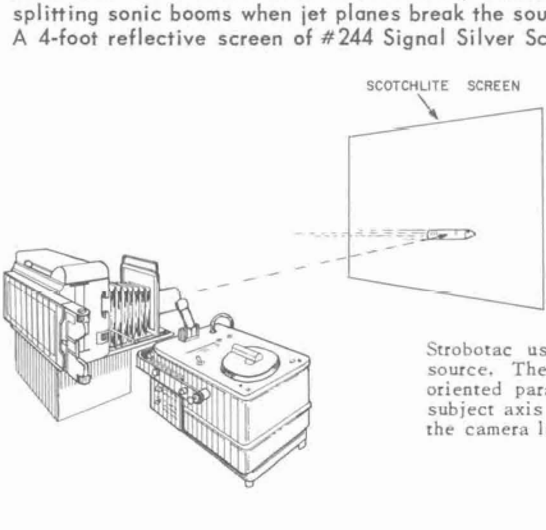

Figure 13.
Application of an auxiliary reflector to the Strobotron.

Figure 14. Shock-wave photography with a Scotchlite screen. (See Section 5.3.)

(Photograph courtesy of Dr. Harold E. Edgerton, M.I.T.)

This shadow photograph of a .30-calibre bullet being fired from a Springfield rifle clearly outlines the spherical sound wave emanating from the gun's muzzle. In the original photograph, the conical shock layer of compressed air extending back from the bullet's nose can be seen; similar shock waves produce ear-splitting sonic booms when jet planes break the sound barrier.

A 4-foot reflective screen of #244 Signal Silver Scotchlite was located 10 feet from the camera. The rifle was 5 feet from the camera. A 135-mm lens was used at f/4.7 on Polaroid Type 52 positive film (ASA 200). A microphone triggered the high-intensity Strobotac flash.




Strobotac used as a point light source. The spark gap must be oriented parallel to the camera-subject axis and as close beside the camera lens as possible.

This method is considerably more involved and requires semi-permanent deformation of the lamp, but it does provide a superior reflector. Suspend the flash lamp upside down in the silvering solution by gently pressing its prongs into a small rectangular block of balsa wood cut to fit snugly on the inside of a straight-walled glass beaker. Then adjust the block so that the top of the lamp is immersed and the contact prongs and glass bottom are not.

After the silver is applied, remove enough of the coating to form a window for escaping light and cover the remaining silver with clear plastic spray or coil dope. When this is dry, paint the silvered area with an opaque, flat black paint. Some exterior discoloring may be noticed after a few hours of continuous operation, but the reflectivity of the coating should remain high for some time.

## 5.3 SHADOWGRAPH PHOTOGRAPHY WITH A SCOTCHLITE SCREEN.

Shadowgraph photography is a technique used to study intense shock waves and other fluid disturbances of a similar nature. Dr. Harold Edgerton has described a technique for taking such photographs using a Scotchlite screen as a reflective backdrop. For good definition with this method, an intense point light source must be located as close to the camera lens as possible. The Type 1531-A Strobotac is ideally suited for this application.

The bare Strobotron lamp is positioned next to and slightly behind the camera lens as shown in Figure 14, so that light is reflected from the screen back through the subject plane and onto the film. Focus the camera lens sharply on the Scotchlite screen, NOT on the subject itself, and be sure there is at least six inches between the screen and the subject. Sharp density gradients in the fluid surrounding the subject will then show up as dark lines against the brightly lit screen, so that intense shock patterns may be studied. The further the screen is separated from the subject, the darker the shock pattern will appear in the photograph, and, of course, the less sharp the subject outline will appear for a given depth of field.[1]

---

[1]See Edgerton, "Shock-Wave Photography of Large Subjects in Daylight," Review of Scientific Instruments, Vol 20, No. 2, February, 1958, p 121, and also Hyzer, op. cit., pp 424-429, for additional information on shadowgraph photography and Edgerton's technique.

section 6

# Single-Flash Photography

## 6.1 GENERAL.

This simple form of high-speed photography is commonly used for taking a single picture of a rapidly moving object in some position of particular interest. First the camera shutter is opened completely, then the Strobotac or Strobolume is flashed once to expose the film, and the shutter is closed again. The subject will be "stopped" and photographed in the position it occupies at the instant the strobe lamp flashes. There are innumerable industrial applications for single-flash photography in the study of high-speed phenomena, and pictures taken in this manner have helped to solve many puzzling problems. An excellent example of this technique is the series of a milk drop splashing on a hard surface (see Figure 15).

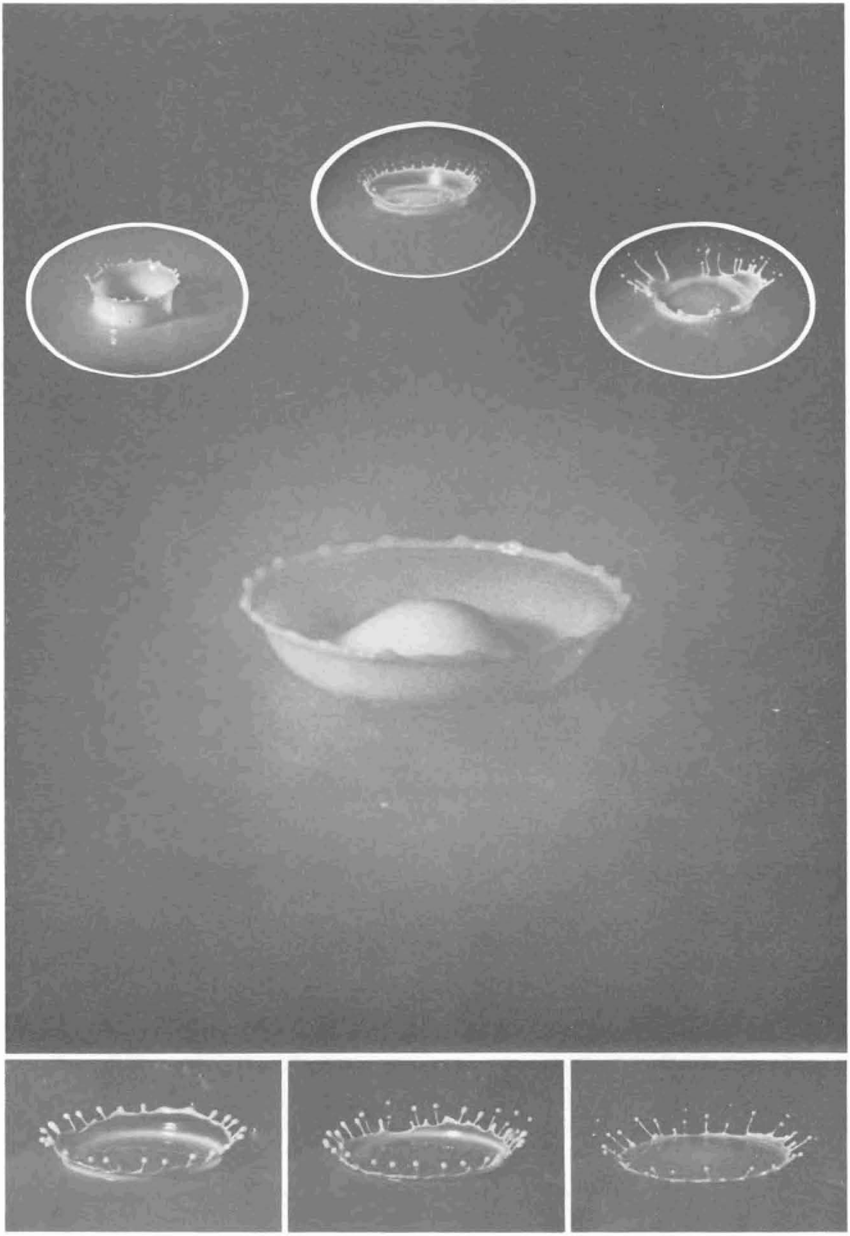
## 6.2 TRIGGERING THE LIGHT SOURCE.

One of the most difficult problems in single-flash photography, and indeed in all high-speed photo-instrumentation work, is to fire the strobe lamp at the proper time to freeze the subject in the desired position. If the subject's position is not critical to the photograph, the light may be flashed at a random time and the usefulness of the picture will not suffer. An example might be a photograph of the spray pattern formed by a hydraulic nozzle, or of a stream of water from a faucet (see Figure 16). But if the subject moves cyclically and must be photographed at a particular point in its cycle, the light flash must be synchronized to its motion.

The particular scheme used to provide a trigger signal depends on the nature of the subject, and considerable ingenuity may be exercised in devising simple, yet effective triggering circuits. Any arrangement can be used that will provide an electrical pulse or a contact "make" or "break" as required by the light source being used.

As an illustration of the wide variety of schemes that can be used to flash the Strobotac at a precise time, consider the problem of

Figure 15. These jewelled crowns, which show a drop of milk splashing on a hard surface, were made in the light of precisely timed flashes from the Strobotac electronic stroboscope.



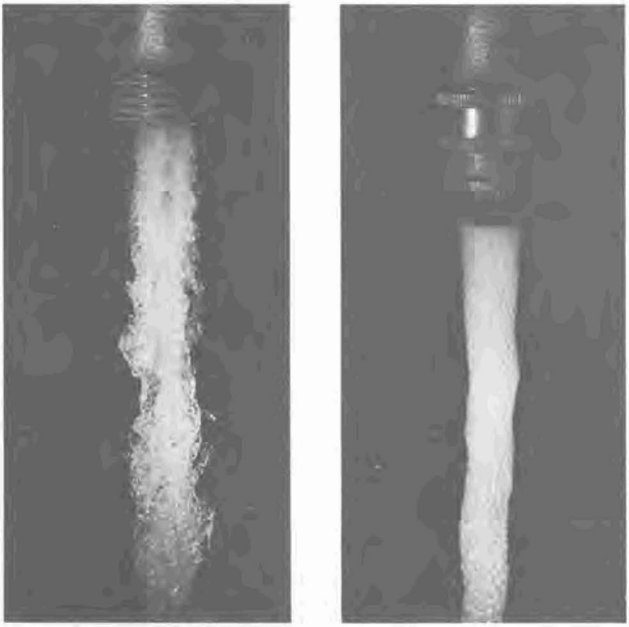


Figure 16. Single-flash photographs of a household water tap, showing the effects of a de-splash attachment. Exposures were made on Polaroid Type 47 film at f/22 with a single, high-intensity Strobotac flash.

photographing a rifle bullet traveling approximately 3000 feet per second (roughly three times the speed of sound). This projectile travels about 36" in 1 millisecond (one thousandth of a second) or 0.036" in 1 microsecond. Since approximately 0.1" would be traversed during the highest intensity flash duration of the Strobotac, and this movement would blur the subject, the highest speed (Low Intensity) flash position should be used.

One of the simplest triggering methods is to fire the bullet at a thin, taut wire connected to the Strobotac INPUT terminals. The lamp will flash a few microseconds after the wire severs (with RPM control fully clockwise) so the camera and lamp reflector should be aimed just past the contact wire.

Alternatively, one can construct a contact closure sensor by gluing two strips of metallic foil on opposite sides of a small circular hole in a thin piece of paper card, and then connecting wires from these foil strips to the INPUT terminals. When a bullet is fired through the card, it momentarily closes the circuit between the two foil strips and this contact closure triggers the Strobotac. The inverting circuit of

Figure 5 would probably be necessary to keep the time delay to an acceptable minimum. Two flexible metal strips separated by a small air space might be used as a contactor in a similar fashion.

A third means of providing an electrical trigger pulse might utilize a photoelectric cell and a light beam. The Type 1536-A Photoelectric Pickoff is suitable for a multitude of these synchronization schemes. Some professional bullet-timing devices also operate on this principle, and they are capable of supplying trigger pulses to the Strobotac.

Another technique which requires no physical contact with the bullet is to use a microphone and an audio amplifier, such as those found in phonographs or sound-movie projectors, to provide a trigger pulse. (See page ii.) The General Radio Type 1551-C Sound-Level Meter can be used as a self-contained sound sensor to drive the Strobotac.

With any of these four methods, the timing of the flash can be adjusted by changing the distance between the firearm and the trigger sensor (foil-covered card, microphone, photo-cell, etc.). A microphone, for example, must be moved slightly more than a foot away from the gun to delay the light flash one thousandth of a second. (Sound travels one foot through air in about 0.9 millisecond.) The Type 1531-P2 Flash Delay provides a wide range of continuously variable time delay and is extremely convenient to use as a delay-timing device.

Variable-reluctance proximity pickups (magnetic pickups) make ideal synchronization sensors for many applications.* These devices produce a small electrical pulse when ferrous material (iron, steel, magnetic alloys, etc.) is rapidly passed close by them (within a fraction of an inch). This pulse, when amplified and fed to the trigger circuit of the Strobotac, can be used as a precise time reference for synchronization purposes. The Flash Delay will operate directly from a low amplitude pulse of this nature, making an additional amplifier unnecessary. Usually the pickups can be most conveniently mounted near a rotating gear or a spinning wheel with metallic spokes, but a wide range of triggering schemes is possible with these units.

## 6.3 LOW AMBIENT LIGHT CONDITIONS.

When single-flash photographs are taken in a darkened room, the camera shutter may be left open for a considerable period of time without fogging the film. If the shutter is equipped with a "Time" or

*A wide variety of variable-reluctance pickups are available from Electro Products Laboratories, Inc., 4501 North Ravenswood Avenue, Chicago 40, Illinois.

"Bulb" setting, it may be opened manually, held open until the light flash can be conveniently triggered (usually by the object being photographed, as outlined in the previous section), and then manually closed. Otherwise, use the slowest available shutter speed to minimize synchronization difficulty.

## 6.4 HIGH AMBIENT LIGHT CONDITIONS.

It is not always feasible to make a single-flash photograph in a darkened room, and shutter speeds must be fast enough to keep film exposure from ambient light down to an acceptable level. Frequently, the most convenient means for accomplishing this is to use a camera with built-in flash synchronization contacts and to trigger the light source directly from those contacts. This technique is useful if the time relationship of the light flash to the moving subject is not critical, but it is almost impossible, for instance, to snap a camera shutter manually at the proper time to photograph a passing bullet.

If ambient light cannot be reduced to a level permitting manual shutter release with longer exposure times as described earlier, it will be necessary to synchronize the triggering of the camera shutter, as well as the light flash, with the subject's motion. Usually this can be accomplished with an electrically operated shutter-release solenoid on the camera with electrical signals used to release the shutter and trigger the light source. These devices are available as accessories for most press cameras, and there are several units sold for adapting older cameras for flash photography. A competent camera repairman should install the device selected.

When high-speed repetitive motions are being photographed, the single-flash feature of the Type 1531-P2 Flash Delay permits the use of relatively fast shutter speeds, with a consequent reduction in exposure from ambient light. See Section 2.3 for a complete description of the methodology.

Cameras with focal-plane shutters are usually not satisfactory for use under high ambient light conditions, because the film frame must be completely uncovered for exposure at the instant the light flash occurs. Most focal-plane shutters do not expose the entire film frame at one time except at extremely slow shutter speeds, and overexposure then becomes a problem.

section 7

# Multiple-Flash Photography

## 7.1 STATIONARY FILM.

Frequently it is desired to observe a sequence of high-speed events in order to study the relationships between them, and a series of single-flash photographs either is unnecessarily difficult to obtain or will not display the desired information in an easily processed form. Under these circumstances, a multiple exposure on a single film frame often satisfies both requirements well.

For example, suppose it is desired to measure the angular velocity and acceleration of a rotating shaft, perhaps as a first step in determining the transient characteristics of a load being driven by the shaft. If one end of the shaft is accessible, this can be easily accomplished by making a single multiple exposure of one shaft revolution with the Strobotac and observing the sequential position of a mark on the periphery of the shaft.

The simplest technique for securing this photograph would be to set the Strobotac at a uniform flash rate and the camera shutter speed at the time required for one complete revolution. The camera can then be focused on the shaft end and the shutter tripped at a random time, so no synchronism with the shaft is necessary. The time between light flashes is equal to the time lapse between the shaft positions indicated by the sequential mark positions on the film, and this information can be reduced to yield both angular velocity and acceleration measurements. Details of a sample problem and data reduction calculations are presented in Figure 17 to illustrate the techniques involved.

This method can be used to make a wide variety of measurements under a host of different conditions. Linear translation can be studied as easily as rotation, and many complex motions can be analyzed quickly and inexpensively in this manner.

A multiple-exposure photograph can also be made by opening the camera shutter manually, triggering the flash in synchronism with various positions of the subject being photographed, and then closing the shutter again. This method is useful when the subject positions being studied occur at irregularly spaced time intervals so that a constant Strobotac flash rate cannot be utilized.

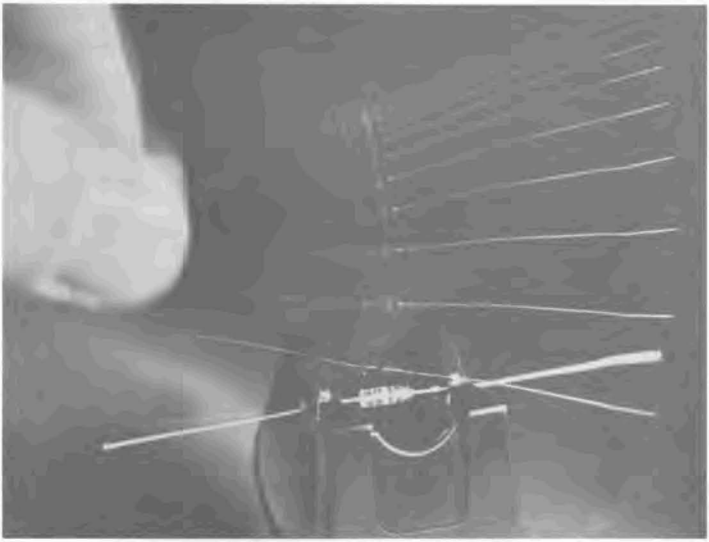
Multiple-flash exposures can be useful for advertising purposes as well as for scientific work. Figure 18 shows how a simple, easily obtained illustration can lend eye-catching appeal to what otherwise might be a run-of-the-mill promotional piece.

## 7.2 MOVING FILM.

The second major method for photographic recording of sequential high-speed events utilizes multiple-flash exposure of a moving film. The Strobotac flash "stops" the motion for each successive frame, and no mechanical shutter is required under low ambient light conditions. (See Figure 19.) Many types of cameras can be modified to transport the film at the desired speed.

High-speed cameras, such as the Wollensak "Fastax", can be adapted for multiple-flash photography by locking the shutter open or removing the shutter assembly. These cameras are capable of moving

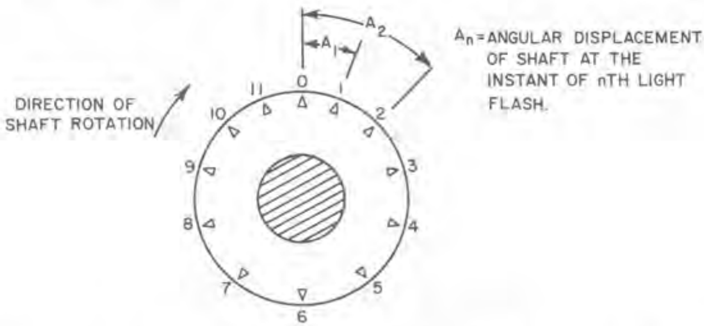
(Continued on page 37.)



(Photograph courtesy of Daymarc Corporation, Waltham, Massachusetts)

Figure 18. Multiflash photograph of a semiconductor diode being attracted to a magnetic Daymarc Diode Clip.

Figure 17. Multiple-flash analysis of shaft rotational motion.




Typical pattern obtained from a multiple-flash photograph of the end of a moving shaft. A single bright mark placed on the shaft's periphery reveals its position at the instant each Strobotac flash occurs.

Given: Average angular velocity = 1800 rpm = 10.8° per millisecond
Strobotac flash rate = 21,600 flashes per minute = 12 flashes per revolution
$t_p$ = time between Strobotac flashes = 2.78 milliseconds
Camera shutter speed approximately 1/30 second

To determine the shaft's average angular velocity at different positions, measure the angles between adjacent mark positions on the photograph and divide by $t_p$. Consider this average value over each displacement interval as the approximate angular velocity at the midpoint of the interval. Since this example is symmetrical, only half of the calculations need be made. For example:

| Angles Measured From Photograph | | | Average Angular Velocity In Degrees Per Millisecond (Angle/$t_p$) | Shaft Displacement At Midpoint Of Interval |
|---|---|---|---|---|
| $A_1$, $(360-A_{11})$ | = | 21° | $W_{1,0} = 7.55$ | 10°, 350° |
| $(A_2-A_1)$, $(A_{11}-A_{10})$ | = | 24° | $W_{2,1} = 8.63$ | 33°, 327° |
| $(A_3-A_2)$, $(A_{10}-A_9)$ | = | 28° | $W_{3,2} = 10.1$ | 59°, 301° |
| $(A_4-A_3)$, $(A_9-A_8)$ | = | 32° | $W_{4,3} = 11.5$ | 89°, 271° |
| $(A_5-A_4)$, $(A_8-A_7)$ | = | 36° | $W_{5,4} = 12.9$ | 123°, 237° |
| $(A_6-A_5)$, $(A_7-A_6)$ | = | 39° | $W_{6,5} = 14.0$ | 160°, 200° |

Figure 17. (Continued)

Angular acceleration may be computed in a similar fashion from these angular velocity data points, e.g.:

| Angular Acceleration (Degrees Per Millisecond$^2$) | | Shaft Displacement Midway Between Data Points |
|---|---|---|
| $(W_{1,0} - W_{12,11})/t_p$ = | 0 | 0° |
| $(W_{2,1} - W_{1,0})/t_p$ = | 0.39 | 22° |
| $(W_{3,2} - W_{2,1})/t_p$ = | 0.53 | 46° |
| $(W_{4,3} - W_{3,2})/t_p$ = | 0.50 | 74° |
| $(W_{5,4} - W_{4,3})/t_p$ = | 0.50 | 106° |
| $(W_{6,5} - W_{5,4})/t_p$ = | 0.40 | 142° |
| $(W_{7,6} - W_{6,5})/t_p$ = | 0 | 180° |
| $(W_{8,7} - W_{7,6})/t_p$ = | -0.40 | 218° etc. |

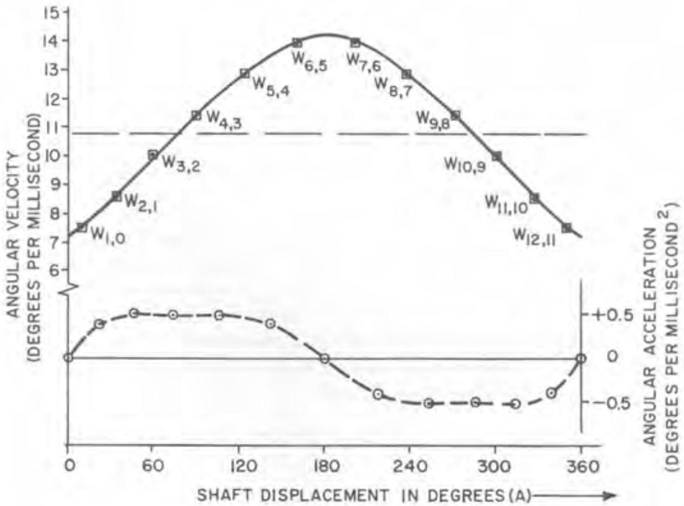
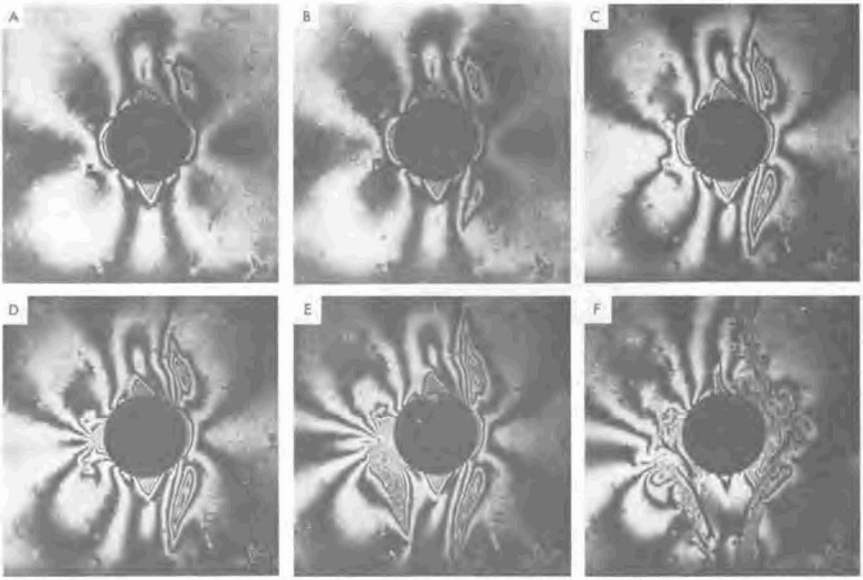
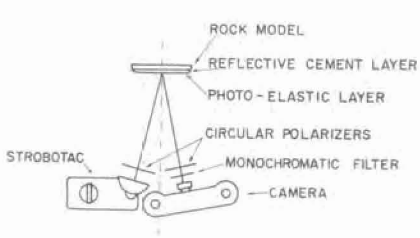


Figure 19. Dynamic redistribution of stress in a rock model undergoing fracture.




(Photographs courtesy of E. Hoek, National Mechanical Engineering Research Institute, Pretoria, South Africa.)




A series of multiple-flash, moving-film, high-speed photographs taken with the Strobotac electronic stroboscope to show the dynamic redistribution of stress in a rock model undergoing fracture. The model is a 5-inch-square rock plate, ¼-inch thick, with a ¾-inch-diameter circular hole in the center. It was subjected to vertical stresses ranging from 33,000 lb/sq in. in (a) to 40,000 lb/sq in. in (e) and (f). The lateral stress was held at 0.15 the value of the vertical stress.

The strain patterns were photographed by the birefringent layer technique in which a layer of photo-elastic plastic is bonded onto the surface of the model with a reflective cement. The photo-elastic pattern induced in the layer by strain in the model is then analyzed with reflected polarized light. The monochromatic filter shown in the diagram was a Wratten 77, which passes light of 5461 angstrom units.

These photographs were taken on Ilford HP3 35-mm film (ASA 160) with a Leica Summicron 50-mm lens set at f/2. The Strobotac was set at 300 flashes per minute (3-microsecond exposure), and the film was transported past the lens at 5 inches per second with an oscillograph camera. No shutter was used. Both the camera and the Strobotac were approximately three feet from the subject, as shown in the sketch.

the film past the camera lens at a high rate of speed so that the internal Strobotac oscillator can be used to provide exposure rates as high as 410 frames per second. Considerably higher frame rates can be achieved if the Strobotac is triggered by an external oscillator.

If it is desired to project multiple-flash film strips in a standard movie projector to observe a high-speed event in slow motion, the flash rate must be synchronized with film speed to produce the proper frame spacing. Both the Fastax and Milliken* high-speed cameras may be fitted with small variable reluctance pickups mounted close to a film sprocket wheel to deliver pulses synchronized with the rate of film travel. When the Strobotac is triggered from these synchronized pulses, the exposed frames can be properly spaced on the film regardless of the film speed past the lens. A similar technique could be used to adapt other cameras for taking high-speed movies.

---

* Manufactured by the D. B. Milliken Company, 131 North Fifth Avenue, Arcadia, California.

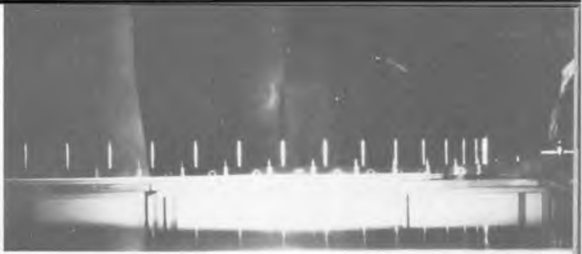
**HIGH-SPEED PHOTOGRAPHY has many uses — esthetic, scientific, industrial. The photographs in these pages illustrate the rich variety of both subject and application.**

Balloons bursting when pricked by a pin — Photos taken using Polaroid 3000-speed film in Land camera. Microphone and amplifier used to pick up sound of burst and to trigger Strobotac flash in dark room, with camera shutter opened manually just before pin enters balloon. *Courtesy of E. F. Sutherland.*

Rip just starting. Microphone was placed close to balloon.

Balloon almost completely collapsed. Flash was delayed compared to previous photograph by placement of microphone farther away from balloon.

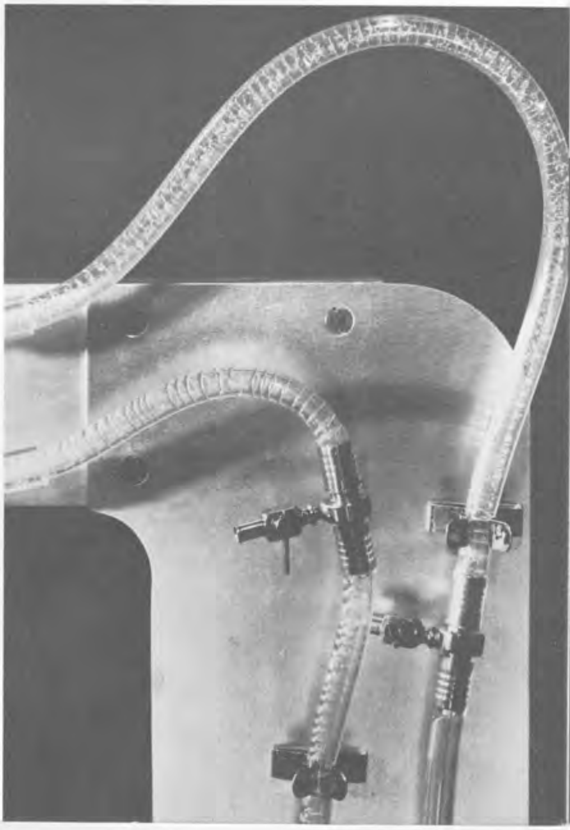
Balloon was first blown up with cigarette smoke, and flash was delayed to allow balloon 'skin' to unwrap itself completely from around its 'filling' of smoke. Collapsed balloon is behind smoke cloud. Note that the balloon unwrapped itself with very little disturbance of the smoke.



Tin can on wooden cart with roller-skate wheels rolling along level surface and being accelerated by a falling weight attached via string and pulley.

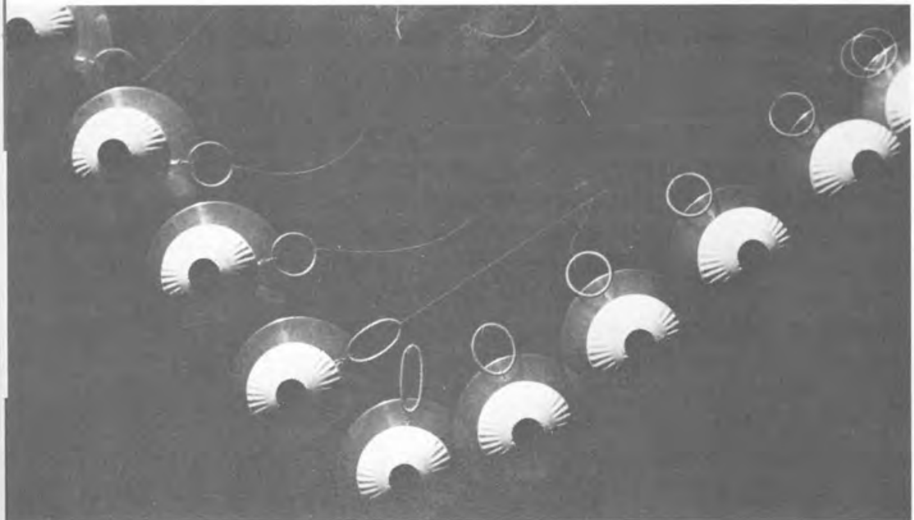
Tin can falling from a magnetic release.

Multiple-flash photographs taken in the classroom help teach the concept of acceleration. With a Polaroid Model 95B camera and Type 46L film, a positive transparency is available for projection (life size) a few minutes after the students see the original action. Camera setting — 13; Strobotac flashing rate — 600 rpm; camera and Strobotac side by side, 20 feet from object. *Courtesy of Mr. Bramwell Arnold, Lincoln-Sudbury Regional High School, Massachusetts.*

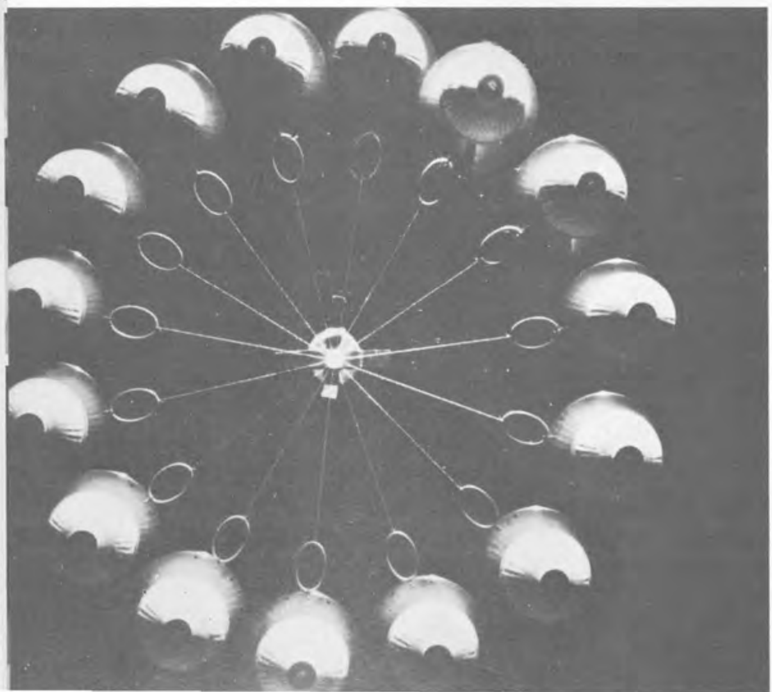


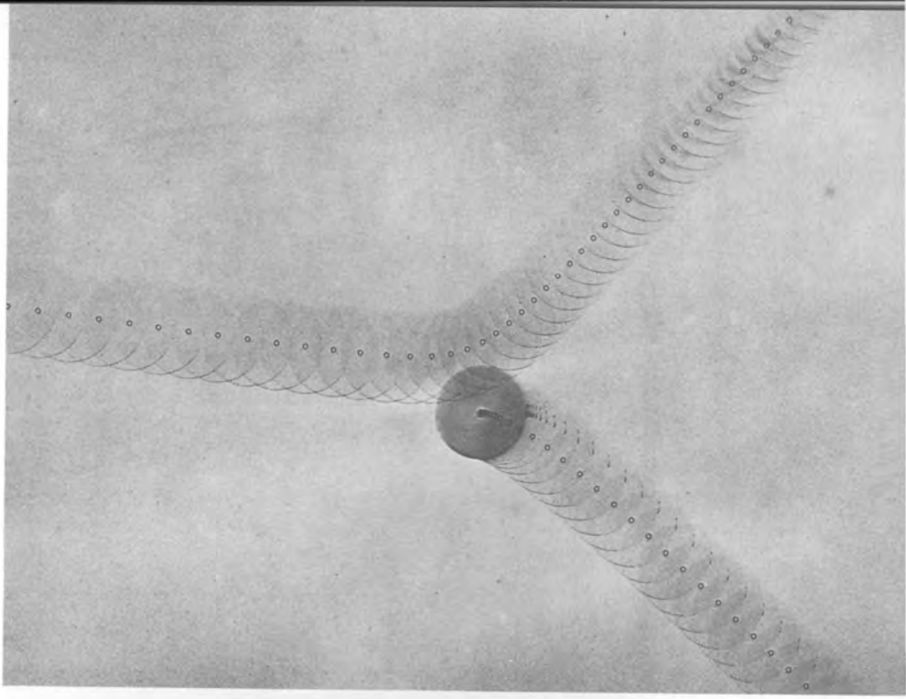
Rapidly moving bubbles of human blood (plasma and red cells) and oxygen in an experimental apparatus for studying improved methods of blood oxygenation by heart-lung machines during open-heart surgery. Photographs such as this allow determination of the bubble sizes, figurations, and number per square inch. *Courtesy of Dr. C. Lloyd Claff, Director of Research, Single Cell Research Foundation, Inc., Randolph, Massachusetts.*

Use of dry-ice pucks on smooth, level surface and multiple-flash photographs to illustrate fundamental principles of physics in educational films. *Courtesy of Educational Services, Inc., Watertown, Massachusetts.*

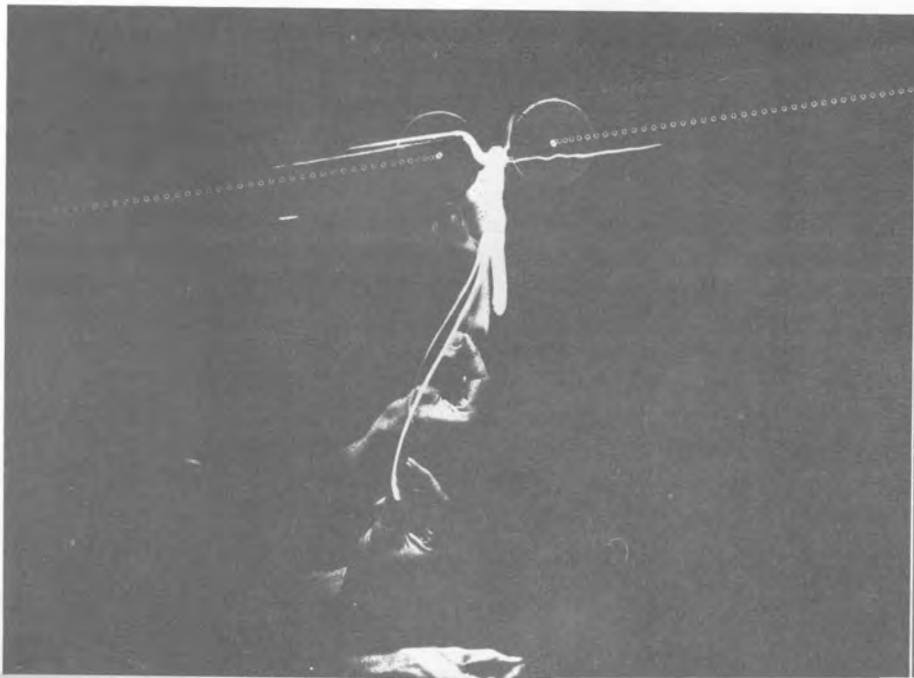


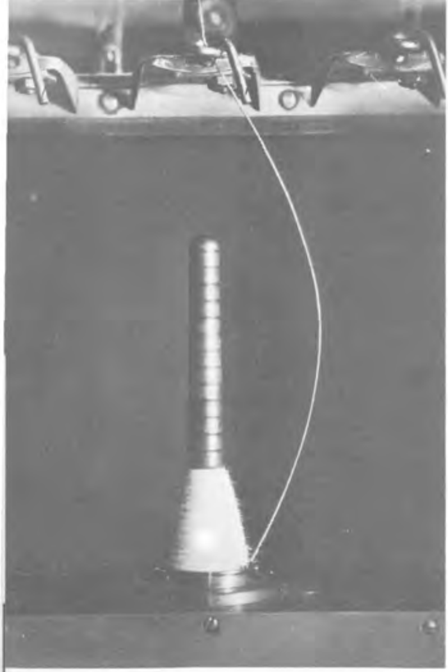
Sliding puck pulled by string at right angles to its direction of motion changes direction but not speed. String is fastened to puck by a rubber ring, which stretches when force is applied. Top photograph shows an abrupt change in direction caused by a brief pull on the string. Photograph below shows circular motion with a constant deflecting force (constant distortion of the rubber ring). Flashes were at one-second intervals. Used in the PSSC film *Deflecting Forces.*





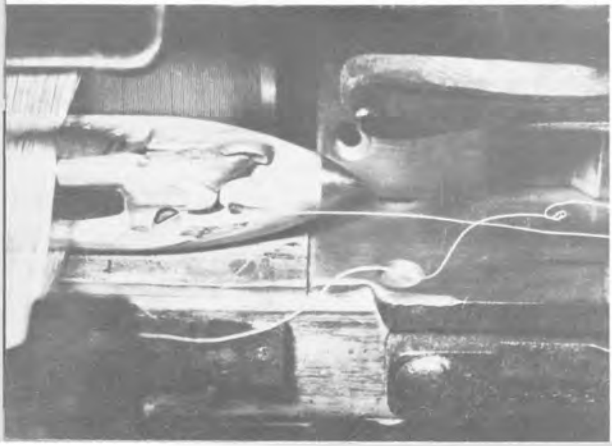
Sliding pucks containing cylindrical magnets oriented for mutual repulsion are used to illustrate the conservation of energy in elastic collisions. Photograph at top shows the reduction of speed and kinetic energy as one puck approaches the other, and analysis shows that this energy is stored in the magnetic field of the pucks. Photograph below shows the 'explosion' which occurs when the two pucks, originally held closely together by a string, are allowed to separate by burning of the string. Quantitative data obtained from analysis of the first photograph enabled a prediction to be made of the final kinetic energy produced by the experiment shown in the second photograph. Flashes here were at 0.1-second intervals. Used in the PSSC film *Elastic Collisions and Stored Energy.*



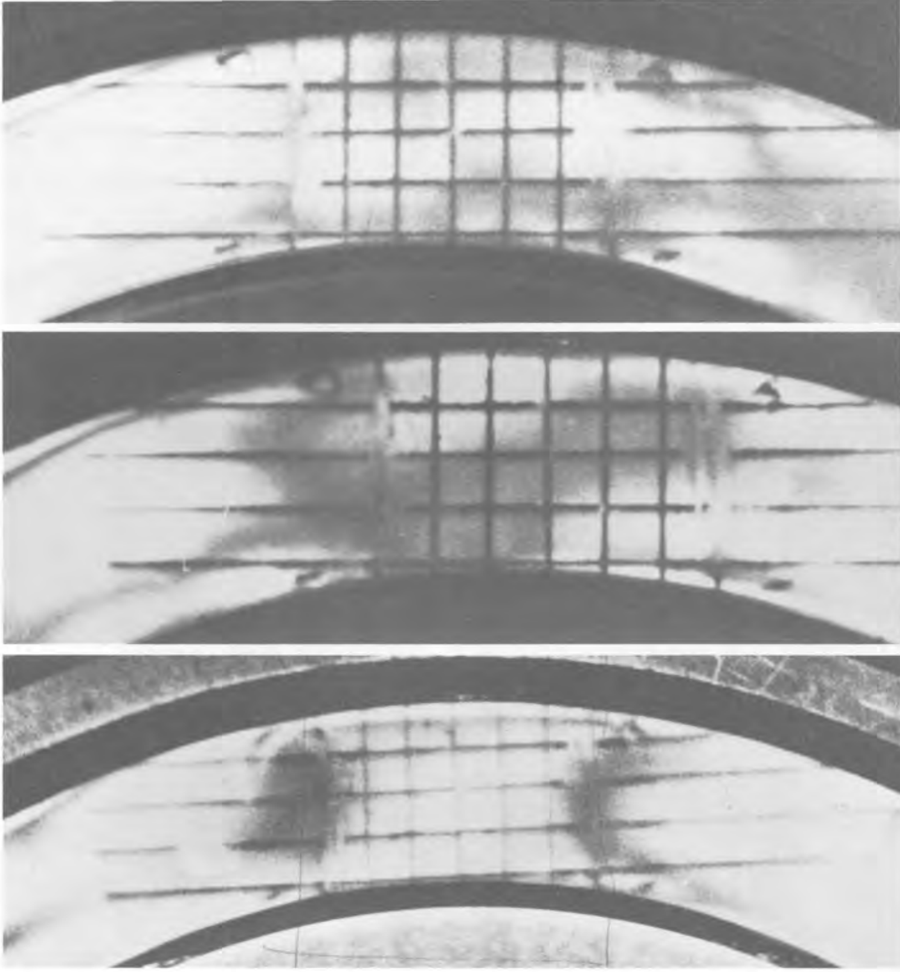


Spindle on a textile spinning frame at approximately 8000 rpm showing 'ballooning' of filament. The ring traveler can be seen at the lower right of the spindle just where the filament leaves the spindle.

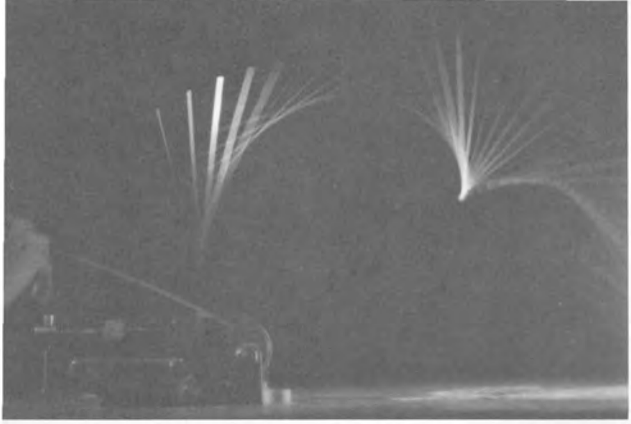
Close-up, single-flash photographs of a textile ring traveler showing its angles of orientation. The left photograph shows the side view of the traveler and the right photograph the top view. Rotation speed of associated spindle was 10,000 rpm, and linear speed of traveler around the 2¾-inch-diameter ring was 120 ft/sec. Type 1536-A Photoelectric Pickoff operated directly from the $\frac{3}{16}$" x $\frac{1}{16}$" traveler passing by. Traveler movement was 0.0005 inch during 3-$\mu$sec flash from Strobotac. A 35-mm camera with 140-mm lens set for f/5.6 aperture was used. *Courtesy of Whitin Machine Works.*



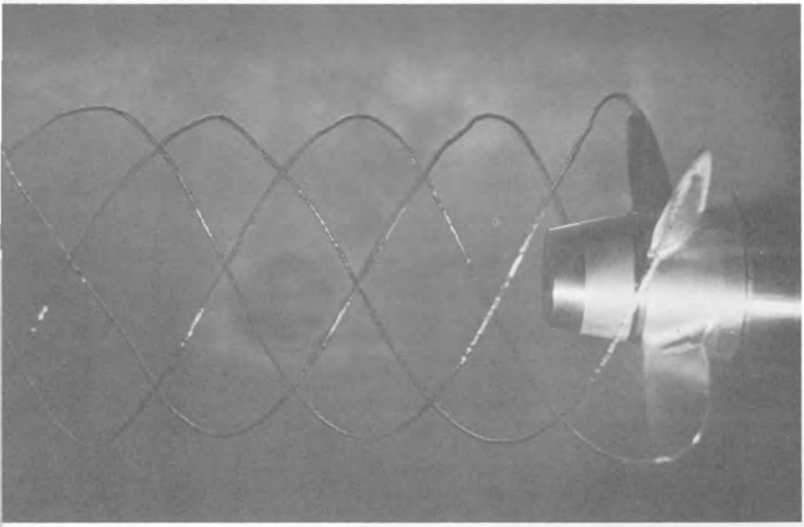
Shuttle in a textile loom just starting on its flight across the loom (traveling toward the left). Behavior of the thread can be clearly seen.



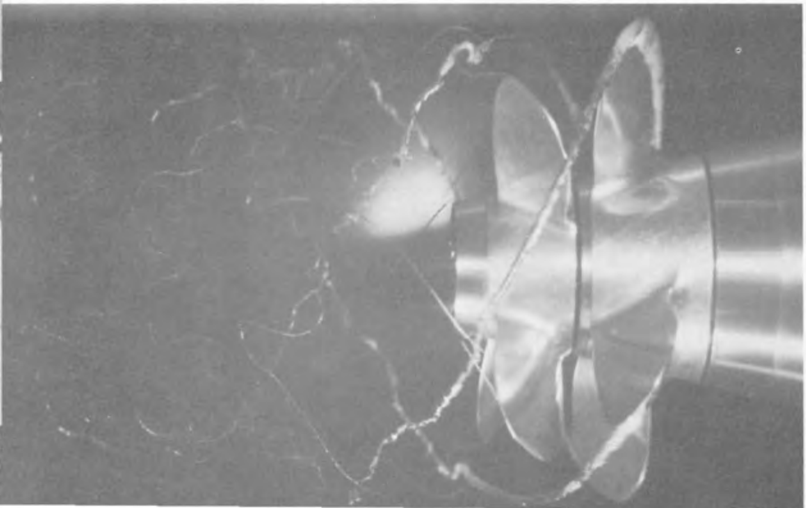
SKF Industries has developed a photoelastic technique for measuring stresses on the cage of a rolling bearing while the bearing is operated under various conditions of speed and load. A layer of birefringent plastic is cemented to the outboard side of the cage by means of a reflective adhesive and is illuminated by polarized stroboscopic light, synchronized to the rotational speed of the cage. The light passes through a Polaroid filter (polarizer), through the birefringent plastic material, is reflected by the reflective adhesive, and passes back again through another Polaroid filter (analyzer) to camera. Grid lines drawn on the specimen itself assist in interpreting the photoelastic stress patterns. Owing to the large amount of attenuation along the light path from source to camera in this application, many flashes of the Strobotac are necessary to expose the film adequately for each photograph. Therefore, precise synchronization of the light flash with the rotation of the bearing is essential. This was obtained by means of a Type 1536-A Photoelectric Pickoff and a Type 1531-P2 Flash Delay, which allowed any desired section of the cage image to be positioned in front of the lens. The 0° and 75° isoclinic photographs indicate stress direction. The 45° isochromatic photograph indicates stress magnitude. Zeiss Contarex camera with 135-mm lens and an X1 green filter to produce monochromatic light at the camera. Camera set at f/4 and 8-second exposure and located 4 feet from specimen. Kodak Tri-X film. *Courtesy of SKF Industries, Inc.*

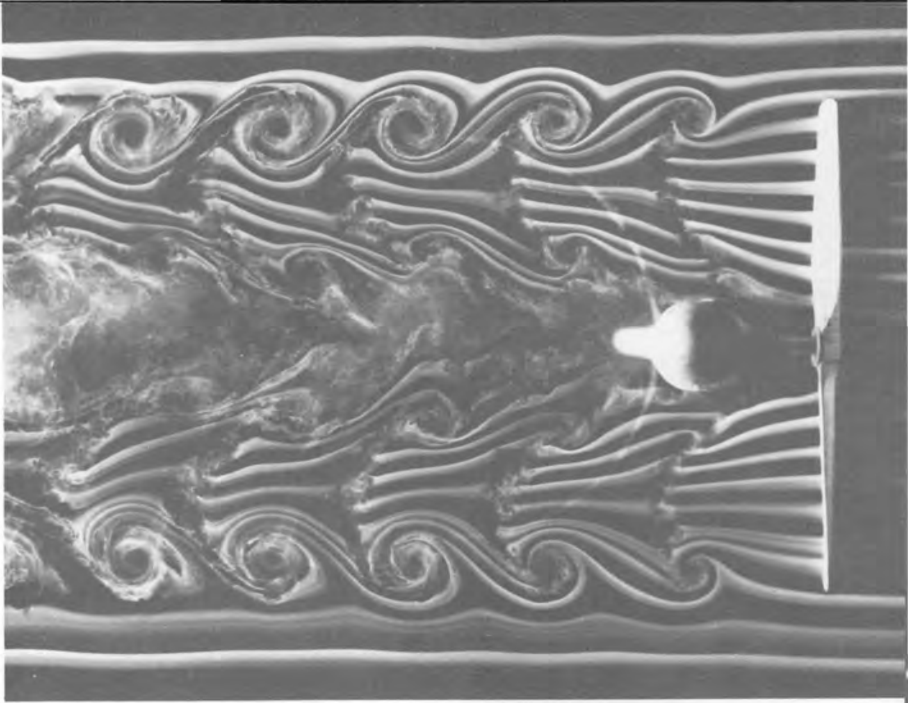


Motion study of flipped stick. Multiple-flash photograph at 100 flashes per second. *Courtesy of Harold E. Edgerton.*

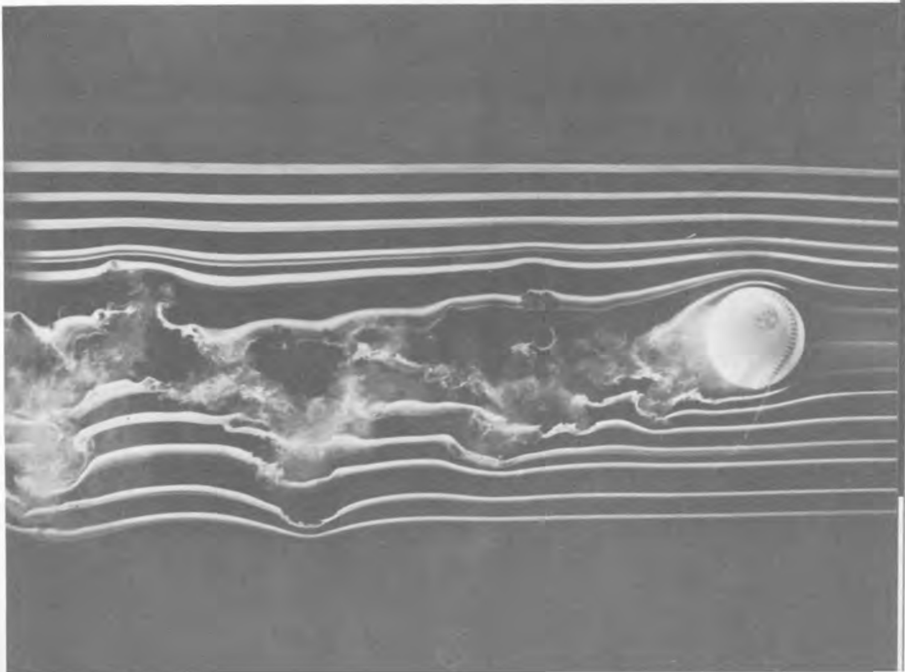


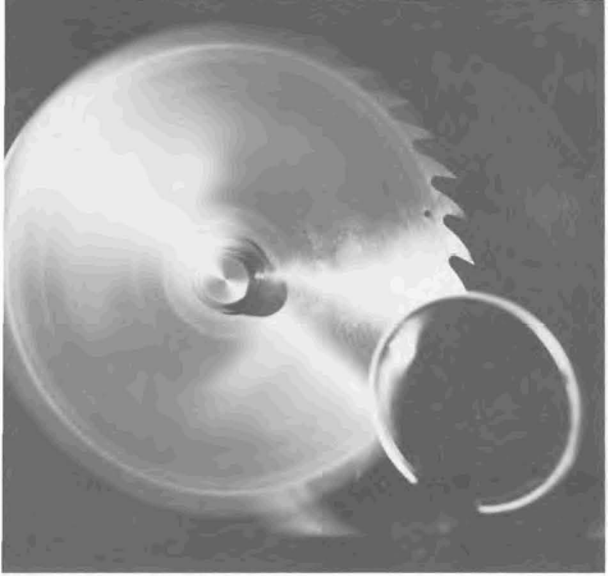
Underwater photographs of propeller cavitation in a test water tunnel. Photograph above shows well defined tip vortex cavitation on a single propeller. Photograph below shows cavitation on a pair of counterrotating propellers. Two Type 1532 Strobolumes were used as the light source. Camera was a 4″ x 5″ Graphic View II.





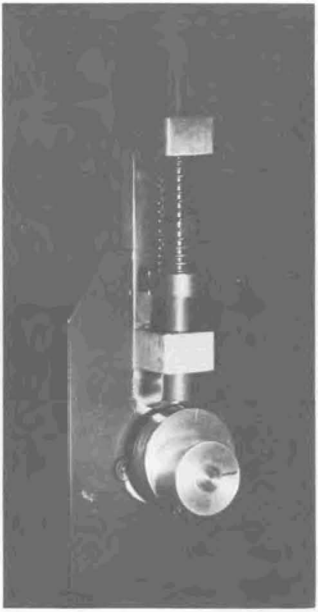
Smoke streams in a wind tunnel can be used to show turbulence patterns. The smoke is produced by the coking of grain straw and is introduced just upstream of antiturbulence screening. It flows with the air stream over and around the model at speeds ranging from 15 to 175 ft/sec. Photographs are taken through a transparent section in the side of the wind tunnel. Photograph above shows a propeller rotating at 4080 rpm with blade pitch set for best rate of climb and air speed about 45 ft/sec. Photograph below is of a spinning baseball, showing Magnus Effect, which causes its path to be curved. *Courtesy of Professor F. N. M. Brown, University of Notre Dame.*

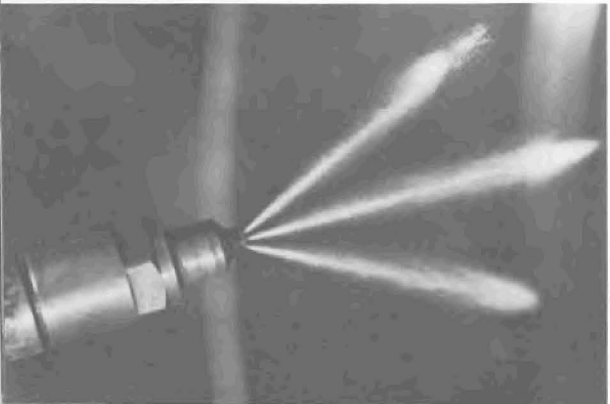




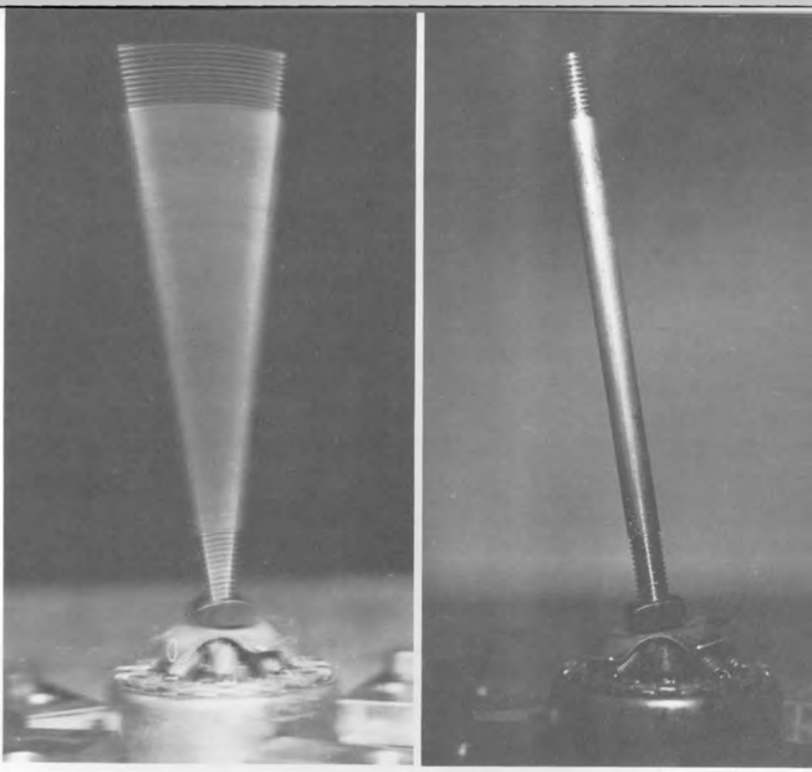
An 8-inch circular-saw blade rotating at 3450 rpm. Left side of blade appears blurred due to exposure under steady light directed only at that side, while right side appears stationary, with minute surface scratches clearly defined, under the 0.8-microsecond flash of the Strobotac.

Study of cam-follower bouncing action when cam rotates above a critical speed. Photograph at left was taken under steady light. Photograph at right, taken using a single Strobotac flash, shows cam follower at height of its bounce.



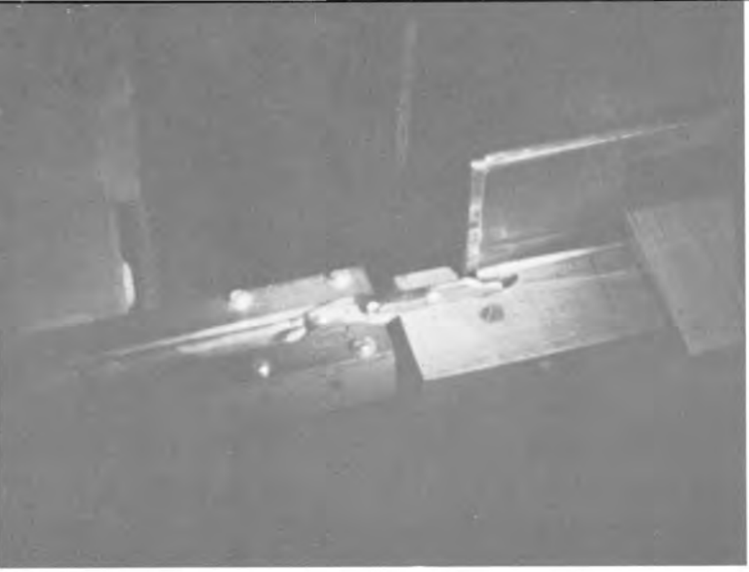


Spray pattern of diesel fuel-injection nozzle. With suitable photographic technique and large-scale photographs, such pictures can be used in estimating droplet size and size distribution.



Rod mounted on spring shock mount vibrating on vibration table. Photograph at left under steady light shows amplitude of vibration. Photograph at right was taken with a single Strobotac flash.

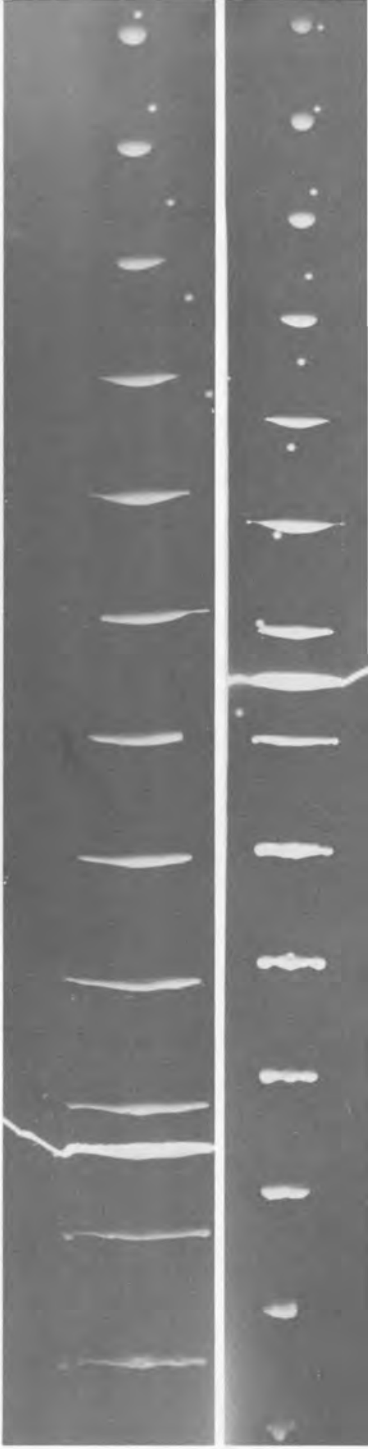

Photograph of label-inspection process with label strip moving at 1000 ft/min. *Courtesy of Wyeth Laboratories, Inc.*



Filling carrier on a high-speed shuttleless loom photographed at the end of a pass into the shed formed by the warp threads. *Courtesy of Draper Corporation.*

Multiple-flash stroboscopic photographs are an aid in teaching violin technique. The frozen images help to analyze and correct posture, hand attitude, and motor skills such as bowing and fingering. To produce the photograph at the right, a neon bulb was attached to the bow to show a continuous path as a supplement to the multiple images. *Courtesy of Dr. Louis C. Trzcinski, University of Nebraska.*

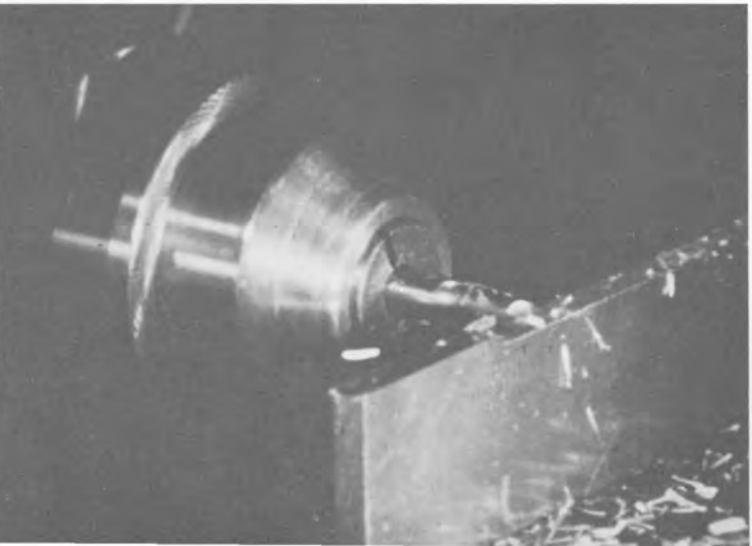
Study of effect of strong transverse electric fields on falling liquid drops, as might occur in rain clouds. Multiple-flash photographs were taken at a Strobotac flashing rate of 700 flashes per minute while a drop of milk fell between two metal plates charged to create a field strength of 10 kv/cm. The drop stretches out as it falls until a discharging spark occurs, after which surface tension pulls it together again. Royal X 4" x 5" sheet film developed in D76. *Courtesy of David C. Eldridge, Edward M. Skinner, and James Tsepas, Andover High School, Massachusetts.*



Shadowgraphs of a bullet passing through a soap bubble filled with Freon-12. A Strobotac was used as a point source by removal of the reflector and orientation of the flash lamp so that the arc of the flash was in line with the direction of the subject and about three yards distant. Instead of a camera, a Polaroid 4" x 5" film back with Polaroid 3000 film was placed 3½" from the bubble on the opposite side from the light source. The flash was triggered by means of a microphone. Photograph below shows bullet entering bubble and the intensification of the shock wave in the Freon-12. Photograph at bottom shows another bullet leaving a bubble, with strong turbulence in its wake. *Courtesy of David C. Eldridge, Edward M. Skinner, and James Tsepas, Andover High School, Massachusetts.*

Combustion study of twin, oscillating gas flames using schlieren technique and stroboscopic light. Reflector of Strobotac was removed so that the flash lamp arc would approximate a point source of light. The parallel light rays produced by the schlieren technique refract differently as they pass through different regions of the flame having different density gradients, thus producing light and dark areas in the photograph. Rate of flame pulsation was twelve cycles per second; rate of stroboscopic flashing was 200 per second. The succession of single images shown in the photograph at left was taken with a streak camera at constant film speed. *Courtesy of Mr. Jon Kelly, M.I.T. Engine Laboratory.*

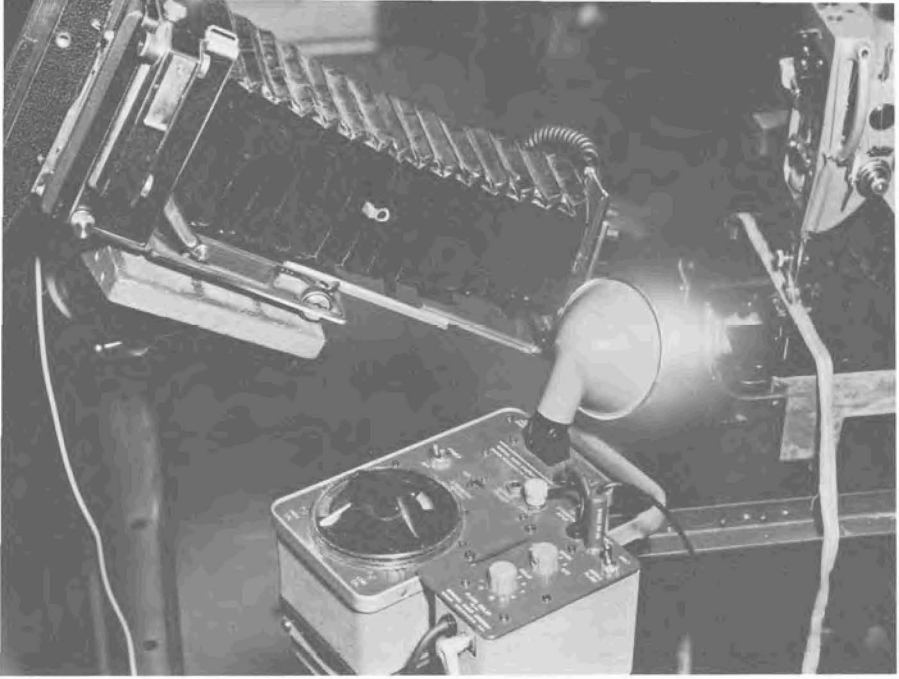
Single 16-mm frame from color motion picture of milling-machine cutter action.



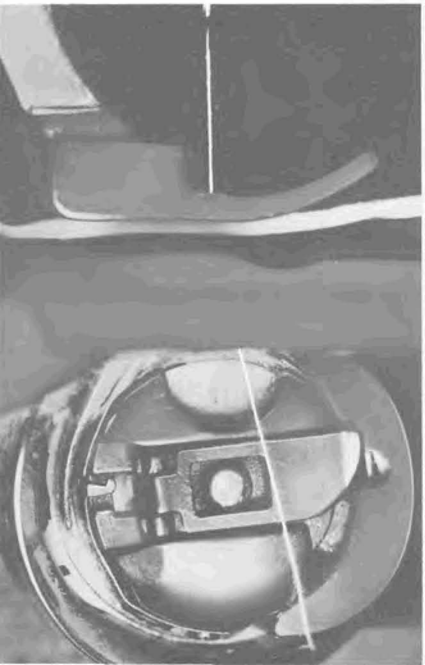
Multiple-flash stroboscopic photography used to track down the specific sources of noise in a textile loom for the purpose of noise reduction. Photograph above shows the setup with Strobotac, camera, end of loom where shuttle flight terminates, and microphone to pick up noise. Other equipment, not shown, includes a dual-beam cathode-ray oscillograph, a photoelectric cell, two pulse generators, and an oscillator. The photoelectric cell detects the approach of the shuttle and triggers the oscillograph sweep and the first pulse generator, which in turn triggers the second pulse generator after a delay long enough to allow the shuttle nearly to reach its deceleration point. The second pulse generator acts as a "gate" to allow the oscillator to trigger a burst of about 17 flashes from the Strobotac at a rate of 500 flashes per second. Photographs are taken in a dark room, with the camera shutter controlled manually.

Photograph below shows shuttle with white flag to mark position. At lower left is a multiple-flash stroboscopic photograph showing the shuttle's white flag as the shuttle decelerates. At lower right is a photograph of the oscillograph screen showing, on the upper trace, the timing of the light flashes in relation to the noise level detected by the microphone and shown on the lower trace.

Analysis of these photographs allows a definite correlation to be made between deceleration and instantaneous noise level, as a result of which the noise-control engineer can learn where effort to reduce noise can most effectively be applied. *Courtesy of Mr. Allen L. Cudworth, Liberty Mutual Insurance Company.*



Study of thread behavior in high-speed sewing machine. Machine speed was 5000 stitches per minute; hook speed was 10,000 rpm. Photograph above shows setup using Linhoff 4″ x 5″ with Polaroid film, Strobotac with attached Flash Delay, and sewing machine (the base of which is cut away to expose the parts underneath). Photograph at lower left shows hook action on thread at a specific phase selected by means of the Flash Delay. Photograph at lower right is taken from a higher angle so as to show the stitch-forming action just under the sewing surface. *Courtesy of The Singer Company.*



# Bibliography

The following sources constitute a reasonably representative sample of available reference materials dealing with subjects pertinent to high-speed photography. They do not represent an exhaustive listing, but most contain bibliographies of their own which, taken together, provide extensive coverage of the field.


Aspden, Ralph L., Electronic Flash Photography, The Macmillan Company: New York, New York, 1959.
(Contains design and application data, an equipment summary, and descriptions of several specialized techniques. Probably most useful to the scientist or photo-instrumentation engineer.)

Castle, John, "The Photographic Response of Several High-Speed Emulsions at Very Short Exposure Times," Photographic Engineering, Vol 5, No. 3, 1954, 189-194.

Castle, J. and J. H. Webb, "Results of Very Short-Duration Exposures for Several Fast Photographic Emulsions," Photographic Engineering, Vol 4, No. 2, 1953, 51-59.

Chesterman, W. Deryck, The Photographic Study of Rapid Events, Clarendon Press: Oxford, England, 1951.

Collins, R. B. (ed.), Third International Congress on High-Speed Photography, Butterworths Scientific Publications, Ltd.: London, England, 1957.

Courtney-Pratt, J. S., "A Review of the Methods of High-Speed Photography," Reports on Progress in Physics, Vol 20, 1957, 379-432.

Eastman Kodak Company, KODAK Reference Handbook: Rochester, New York.
(Several loose-leaf volumes contain individual booklets covering practically every phase of photography. An invaluable reference.)

Eastman Kodak Company, Schlieren Photography: Rochester, New York, 1960.
(Explains the basic schlieren method and describes several systems for taking schlieren photographs. An excellent primer on the subject.)

Edgerton, Harold E., "Shock-Wave Photography of Large Subjects in Daylight," Review of Scientific Instruments, Vol 29, No. 2, February, 1958, 121.
(Describes Edgerton's method for making shadow photographs of shock-wave patterns using a reflective Scotchlite backdrop.)

Edgerton, Harold E. and James R. Killian, Jr., Flash! Seeing the Unseen By Ultra High-Speed Photography, 2nd edition, Charles T. Branford Company: Newton, Massachusetts, 1954.
(Recommended for beginners and experts alike. A true classic from both scientific and artistic standpoints, this book contains the finest collection of original high-speed photographs ever published. It stimulates a wealth of ideas.)

General Radio Company, Operating Instruction Manual, Type 1531-A Strobotac® electronic stroboscope, Form 1531-0100.

General Radio Company, Operating Instruction Manual, Type 1532-D Strobolume, Form 1532-0100.

Henney and Dudley (ed.), Handbook of Photography, Whittlesey House: New York, 1939.
(A standard reference for the professional photographer.)

Hyzer, William G., Engineering and Scientific High-Speed Photography, The Macmillan Company: New York, New York, 1962.
(Contains an excellent chapter on Techniques in High-Speed Photography and offers a thorough, comprehensive summary of modern equipment and methods.)

Jones, George A., High-Speed Photography, Its Principles and Applications, Chapman & Hall, Ltd.: London, England, 1952.
Also published by John Wiley & Sons, Inc.: New York, New York, 1952.
(An exhaustive presentation of equipment and techniques developed to date, along with some applications data.)

Laue, Eric G., "A Strobe-Control System For Motion-Picture Cameras," Jet Propulsion Laboratory, California Institute of Technology: Pasadena, California, Memorandum No. 20-95, 1954.

Mees, C. E. Kenneth, The Theory of the Photographic Process, revised edition, The Macmillan Company: New York, New York, 1954.
(A highly technical reference most useful to the photochemist or experienced film processor.)

Neblette, C. B., Photography, Its Materials and Processes, 2nd edition, D. Van Nostrand Company, Inc.: Princeton, New Jersey, 1952.
(A straightforward, easily understood textbook covering practically all phases of photography.)

Palme, Arthur, Speedlights, Construction and Use, American Photographic Publishing Company: Boston, Massachusetts, 1946.
(Directed at the photographer, this book contains a chapter describing in detail several simple methods for synchronizing an electronic flash unit with a camera shutter. Also includes a section with several interesting electronic-flash photographs.)

Society of Motion Picture and Television Engineers, High-Speed Photography, bound reprints from Journal of the SMPTE: New York, New York, 1952-1957.

Society of Motion Picture and Television Engineers, Instrumentation and High-Speed Photography, Vol 1, Series II: New York, 1960.

Tupholme, C. H., Photography In Engineering, Faber and Hyperion Ltd.: London, England, 1945.

Waddell, J. H. and J. W. Waddell, Photographic Motion Analysis, Industrial Laboratories Publishing Co,: Chicago, Illinois, 1955.