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A 4-MICROSECOND FLASHING LIGHT SYNCHRONIZED WITH FRAMING OF MOTION-PICTURE CAMERAS AND ITS APPLICATION IN SCHLIEREN PHOTOGRAPHY

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16. Abstract

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This recording system was developed and operated in schlieren photography of flows in aerodynamic research. This schlieren system has been expanded by the addition of an independent channel that permits visual monitoring of the test conditions at will and independent of the recording system.

The light, controls, and cameras of the recording system are applicable to other studies involving rapid motion such as those encountered in processing and in machinery.

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SUMMARY

A photographic system has been developed and operated wherein a 1000-watt mercury-vapor lamp is flashed in synchronization with the framing of 16-millimeter high-speed and 35-millimeter low-speed cameras. The flash of light has a duration of about 4 microseconds and is triggered either by a generated sinusoidal voltage at high speeds or by a make-break switch at low speeds. The system is capable of flashing at rates from below 10 to about 1400 per second.

This recording system was developed and operated in schlieren photography of flows in aerodynamic research. This schlieren system has been expanded by the addition of an independent channel that permits visual monitoring of the test conditions at will and independent of the recording system.

The light, controls, and cameras of the recording system are applicable to other studies involving rapid motion such as those encountered in processing and in machinery.

INTRODUCTION

Research in high-speed aerodynamics since 1935 (ref. 1) has established two basic requirements of schlieren photography of fluid flows for use in analyzing the test data. Many schlieren installations do not have these features but it is highly possible that the usefulness of the schlieren data could be improved greatly if these features were incorporated. These two requirements are in addition to need for high optical quality and precision alinement of all components. (See appendix.) The first requirement, an obvious one which has long been established, is to produce photographs with exposures in the microsecond range. The short-duration exposures prevent loss of detail in the photographs that otherwise occurs through blurring resulting from movement of flow, equipment, or film. Still photographs with microsecond exposures are taken for a selected set of test conditions with the exception of time, which is a random factor.

The flow often becomes unsteady or oscillatory somewhere within the range of test variables especially in transonic flows. A still photograph obtained of oscillatory flows at a random time within oscillations can be confusing or misleading. The character of the flow can change or diverge within some particular range of a test variable such as Mach number, model attitude, or other time-dependent test factor. While such changes in the fluid flow can be overlooked in still photographs taken at preselected intervals, the changes are more easily detected in sequential photographs or motion pictures that cover the range of the variable. The second requirement for schlieren photography is to obtain sequential photographs or motion pictures at a suitable frame rate to reveal unsteadiness or oscillations of the flow and the character of the oscillations as well as the change in character of flow with change in test variable. These two requirements were accounted for separately in previous work on oscillatory flows reported in reference 2. Still photographs with exposures of about 4 microseconds taken at random times for a given set of test conditions and motion pictures at 5000 frames per second with exposures of 70 microseconds by using a continuous-light source were obtained and used in the analysis in reference 2. This approach produced a large amount of film to be examined and thus proved to be awkward, time consuming, and consequently undesirable for research programs. A solution was obtained by simultaneously satisfying both requirements in one system.

The system used a flashing mercury-vapor lamp having a flash duration of about 4 microseconds. The flash was synchronized with the framing of a 16-mm high-speed camera. The commercially available camera was adapted to generate an oscillatory voltage with a frequency equal to the framing rate. The basic system, its construction, and performance were described and illustrated in reference 3. Since publication of reference 3 in 1953, the electronic equipment has been altered and revised as the need arose in operation to provide greater flexibility by the addition of circuitry to permit regulation of power per flash and to provide an alinement light that is independent of camera operation. The purpose of this paper is to describe the present revised form of the system and a current application to schlieren photography and to provide guidance in the setting up of a schlieren system.

SYMBOLS

a	distance from knife edge to thin lens equivalent of auxiliary or camera lens
b	distance from thin lens equivalent of auxiliary or camera lens to film plane
C	capacitance of power capacitors, farads

d	derivative
d_c	clear aperture of auxiliary or camera lens
d_i	schlieren image diameter in film plane or on viewing screen corresponding to field diameter d_o
d_m	clear aperture of mirrors, inches (meters)
d_o	diameter of field in test region
e	capacitor voltage immediately prior to discharge or at instant of triggering of thyratron
E_o	capacitor voltage after a long charging period
E_1	voltage required to initiate flashing of lamp
E_2	minimum voltage at which lamp will continue to flash
E_3	capacitor voltage immediately after lamp has flashed
f	focal length of mirrors, $f = f_1 = f_2$, inches (meters)
f_1	focal length of collimator, $f_1 = f_2$
f_2	focal length of condenser
f_3	focal length of auxiliary or camera lens
F	focal length-to-diameter or clear aperture ratio
h	height of light-source image perpendicular to knife edge, mils (millimeters)
i_2	image distance for condenser alone
L	axial distance from test region to condenser
m	length of mirror axis from collimator to condenser

M	Mach number
n	flashing rate of lamp or frame rate of camera, $seconds^{-1}$
P	power input to lamp, watts
R	resistance in charging circuit, ohms
R_l	charging resistor in modulator, ohms
s	linear spacing between primary and secondary light sources
t	lapsed time since last flash of lamp, seconds
v	voltage of power capacitor at any time t, volts
w	width of light-source image parallel to knife edge
x	axis perpendicular to mirror axis and to knife edge
y	linear extent of density gradient along mirror axis in test region
β	illuminance on screen or film plane
Δ	change in value of variable
ϵ	base of natural logarithms, 2.718
ρ	mass density of air at point in test region
ρ_o	mass density of air at 0^{o} C and 760-millimeters of mercury
ϕ_1	off-axis angle of collimator – primary source
ϕ_2	off-axis angle of condenser – primary image
ϕ_3	off-axis angle of secondary light source
ω	angular refraction of light in test region in x-y plane (change in angle), arc seconds

Subscripts:

max maximum detectable value

min minimum detectable value

APPARATUS

Scope of Revisions

One of the earliest changes in the original system of reference 3 was dictated by the need to flash sequentially the lamp on demand without operating the recording camera. This feature permitted the alinement of the schlieren system and the recording camera to be adjusted and checked. The next alteration was the incorporation of additional selectable capacitors to permit positive control of the luminous output of the light source and thereby assure proper photographic exposure of the film. The capacitance (ref. 3) was fixed at 0.20 μF. In its present form the capacitance can be varied between 0.10 and 0.85 μF in 0.05-μF steps.

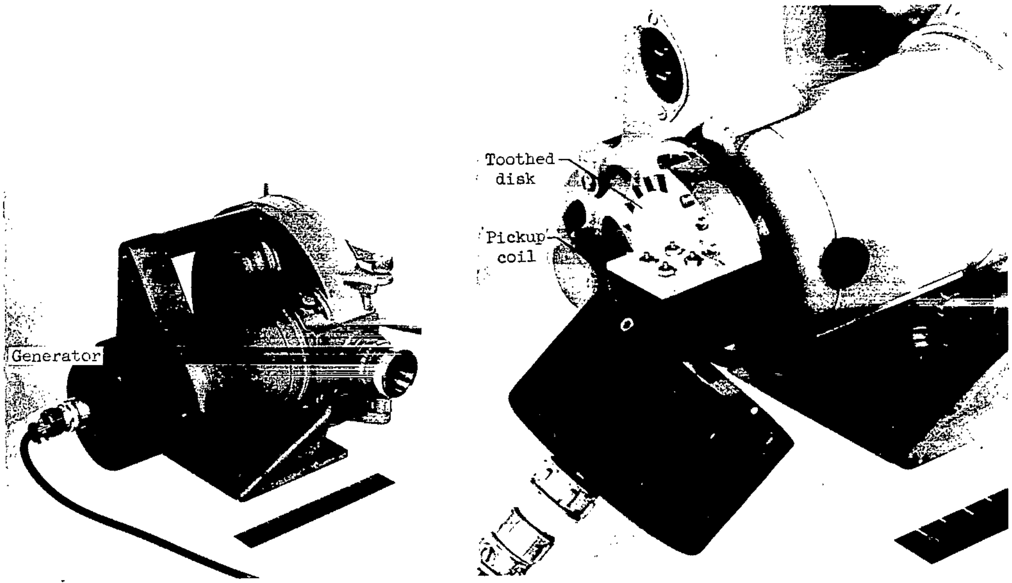
The third change in the electronic system was the installation of a circuit that activated the light source with an external make-break switch at low flashing rates (8 to 20 per second). This alteration permitted operation with either the generated voltage of the 16-mm motion-picture camera or with a simple make-break switch on a 35-mm motion-picture camera. For the 35-mm camera the switch action was synchronized with the shutter opening.

General

The 16-mm and 35-mm cameras used in the system are shown in figure 1. The various components of the flashing-light system are shown in a block diagram in figure 2. Wiring diagrams of the individual electronic components are presented in figures 3 to 6. The light-source housing is shown in figure 7. Connections to the plug-in units of figures 3 to 6 are tabulated in table I.

16-mm Camera

The camera (fig. 1(a)) is a 16-mm Fastax motion-picture camera in which the internal rotating prism that acts as a shutter has been retained. The prism serves a dual purpose: First, by shutter action the prism permits correct adjustment of phasing between signal and film position to place properly the image on the film for projection; second, the rotating prism optically compensates for all slight variations in the time intervals between the time the film is in correct position and the light flashes, inasmuch as the



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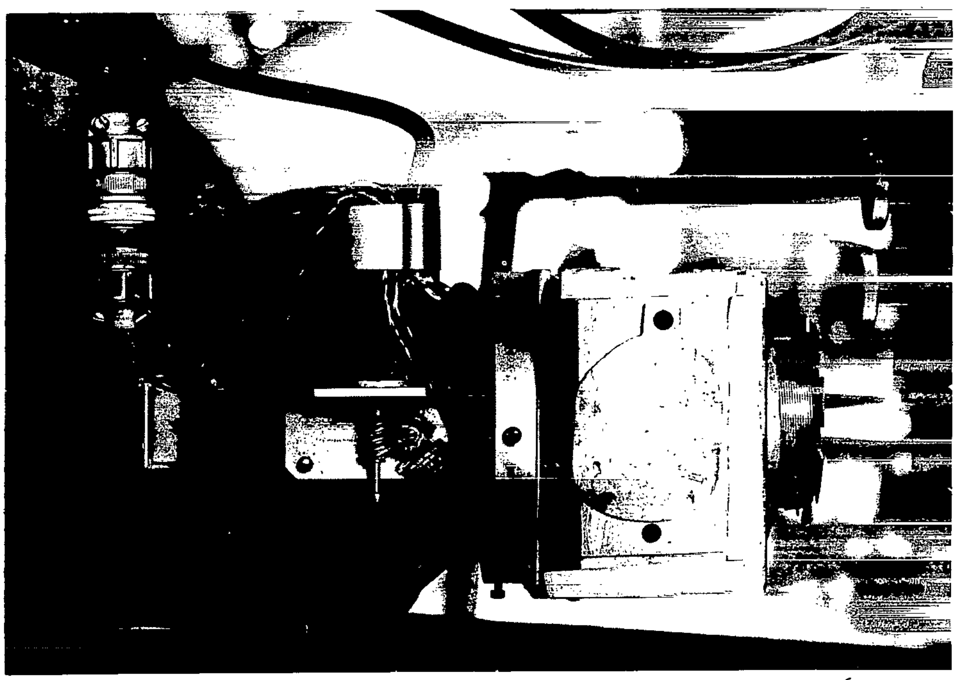
(a) 16-mm camera. (b) Generator cover removed.

Figure 1.- Cameras.



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(c) 35-mm camera.

Figure 1.- Concluded.

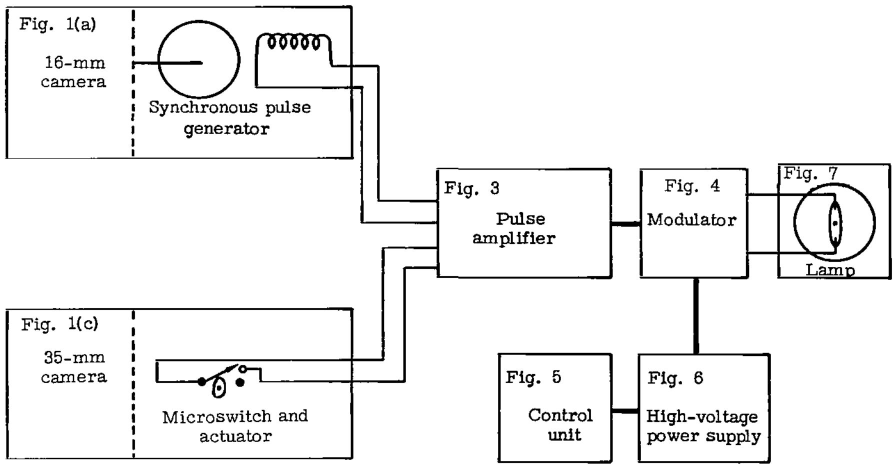


Figure 2.- Block diagram of flashing-light system.

prism optically maintains a truly equal equal spacing between picture centers on the film or provides register between picture formation and film frame.

The camera was modified by attaching a generator to the film drive shaft (figs. 1(a) and 1(b)). The rotating part of the generator consists of a circular steel disk on which teeth have been cut (fig. 1(b)), each tooth corresponding to one frame of the film. Near the disk and on the drive motor frame is mounted the other component of the generator, which is a pickup coil with a permanent magnetic core (also in fig. 1(b)). As the camera operates, the toothed disk rotates and electrical pulses are generated in the coil as each tooth passes the face of the magnet. Phase control between open position of the shutter and flashing of the light is provided by rotational adjustment of the pickup coil with respect to the toothed disk on the camera drive shaft. The adjustment is made while operating the camera at the selected frame rate with a dummy film in the camera, thus simulating the test run to be made. The induced electrical pulses in the coil are transmitted to the pulse amplifier.

35-mm Camera

The 35-mm motion-picture camera as modified and used in this system is shown in figure 1(c). The camera is driven by a constant-speed motor and framing rates from 8 to 20 per second are accomplished by changing the gear ratio of the worm-pinion assembly. The drive shaft on which the pinion is attached has a cam that actuates a normally open microswitch each time the shutter is open. The microswitch with its make-break circuit has a separate input to the pulse amplifier.

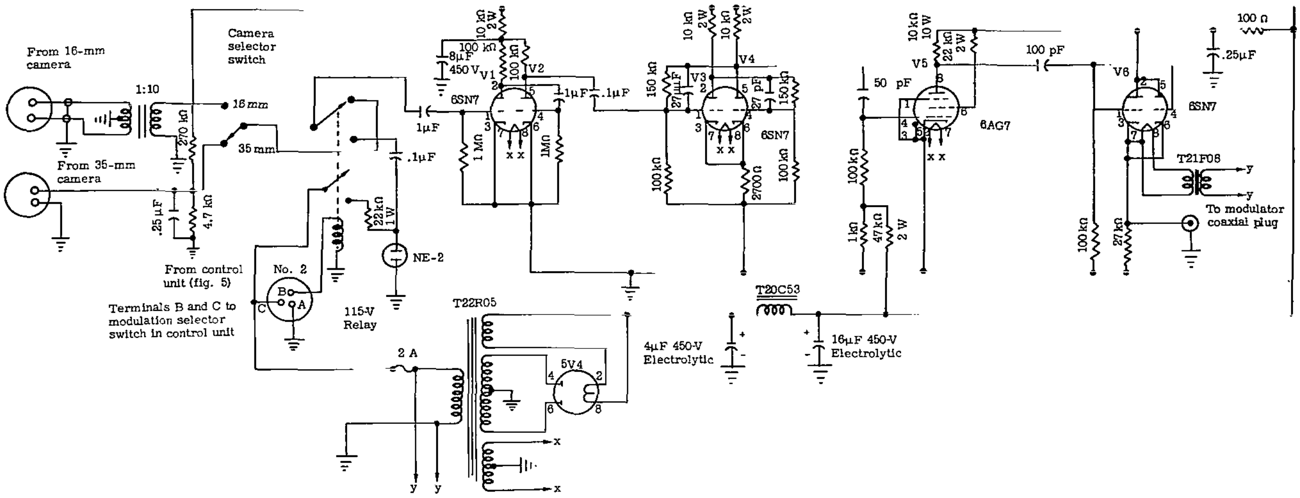


Figure 3.- Pulse amplifier.

Pulse Amplifier

The pulse amplifier is shown in figure 3. The input circuit has been altered from that presented in reference 3 by the addition of the alinement flashing circuit containing the neon-lamp pulser (NE-2) and the circuit for the 35-mm camera. The alinement circuit produces 60 flashes per second and is switchable from the control unit. The signal input circuit has a switch to select the input as either the generated signal from the 16-mm camera or the make-break circuit of the 35-mm camera which is energized within the amplifier. The 16-mm-camera generated signal feeds into a transformer which increases the voltage of the approximately sinusoidal generated low-voltage signal. The 35-mm circuit operates at a higher voltage and does not require the transformer. The signal is further amplified in the first stage (V1), and this amplification is accompanied by distortion of the signal wave form. The resulting signal is fed into the second stage (V2) which is a positive-feedback arrangement in the form of an overbiased multivibrator. This stage produces a square wave having a high rate of rise and fall. The square wave is converted in the third stage (V3) into a series of positive and negative pulses. The amplifier, however, is biased to saturation and the output from the third stage consists of positive pulses only. These positive pulses have a rise rate of about 150 volts per microsecond. The output of the third stage is fed into an impedance converter (V4) which provides low impedance to allow the signal pulses to be transmitted through a coaxial cable to the modulator.

Modulator

The modulator (fig. 4) contains the power capacitors with switches, a hydrogen thyratron tube, and accessory equipment. The pulse signal from the pulse amplifier is

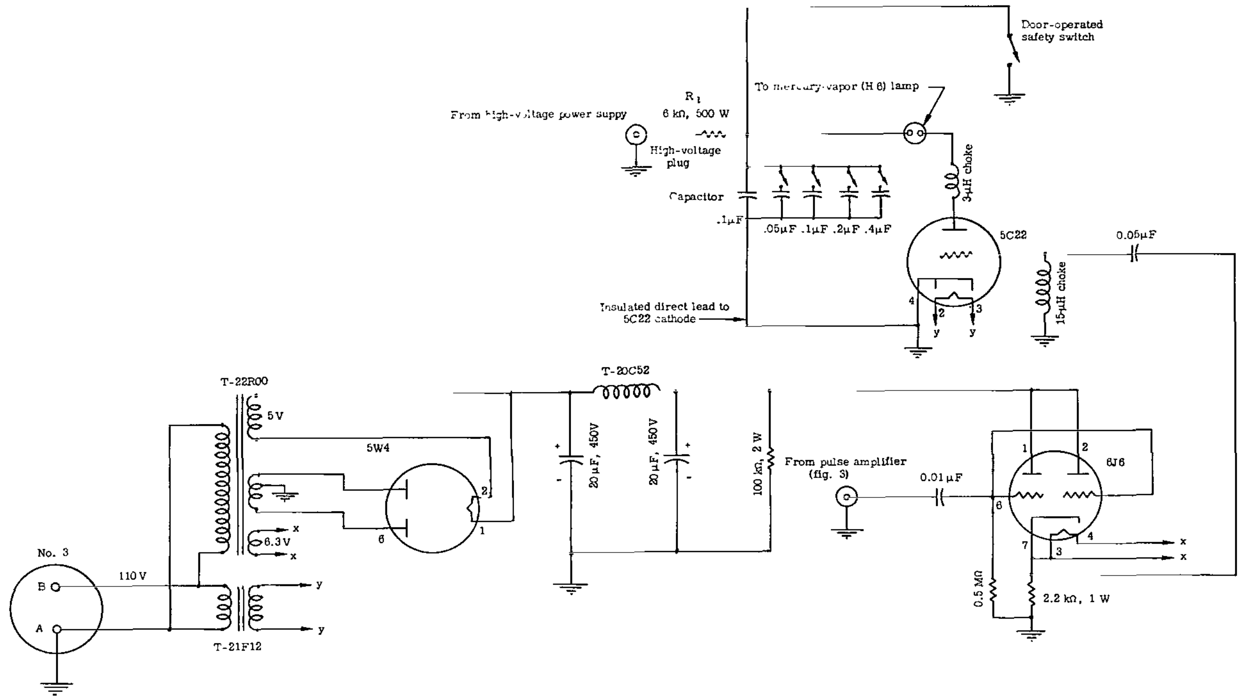


Figure 4.- Modulator.

fed into the modulator and controls the rate at which the thyratron tube discharges the capacitors. The current from the power capacitors is discharged through a 1000-watt mercury-vapor (H6) lamp that provides a flashing light as a source of illumination and, as previously stated, this pulsing light is synchronized with the open position of the shutter of the camera. The current path in the discharge circuit is made short and returned directly to the cathode of the hydrogen thyratron tube to minimize ground currents and radiations which might affect the pulse amplifier and cause erratic operation. The choke coil (3 microhenries) is in series with the lamp to protect the thyratron tube. The coil limits the peak current which may result from stray capacitance in the lamp circuit without appreciably affecting the main pulse. Five power capacitors are installed in the modulator, one of 0.1 μF is permanently connected. The remaining four having capacitances of 0.05, 0.1, 0.2, and 0.4 μF can be connected in parallel through high-voltage switches that permit any of them to be added to or taken out of the circuit. This combination permits any capacitance to be selected between 0.1 and 0.85 μF in steps of 0.05 μF, thereby regulating the intensity of the light output per flash. This feature was one of the alterations made to the original system described in reference 3 to improve its performance and flexibility of operation. These power capacitors are charged to an initial voltage of 3 kilovolts E_0 by the high-voltage power supply.

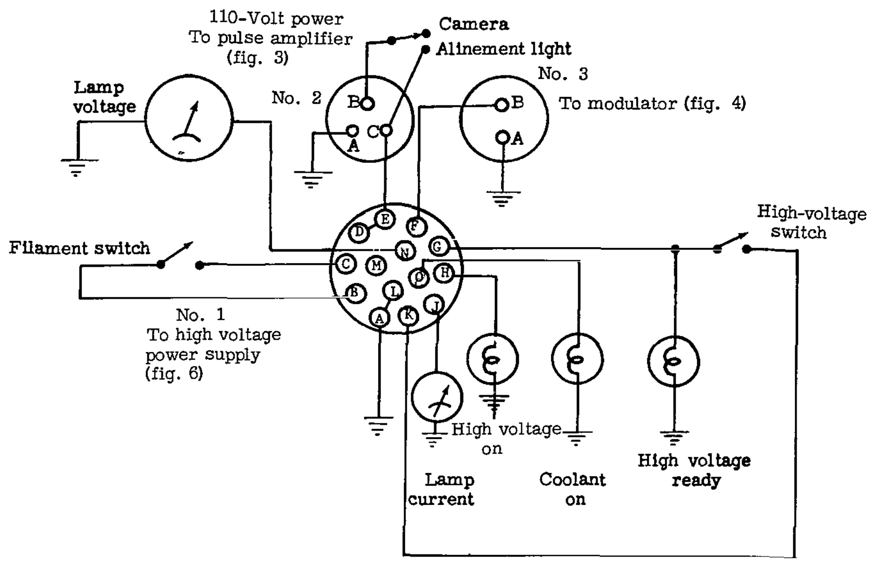


Figure 5.- Control unit.

Power Supply

For convenience, the high-voltage power supply was separated into a control unit (fig. 5) and a power-supply unit (fig. 6). The control unit is separated from the power-supply unit so that it can be placed in a convenient location and contains the switches, meters, and indicator lamps as shown in figure 5. A circuit diagram for the high-voltage power-supply unit is presented in figure 6. This unit converts alternating current at 110 volts into direct current at 3 kilovolts to charge the power capacitors in the modulator. The charging rate is limited by the 6000-ohm 500-watt resistor R_l installed in the modulator (fig. 4) in the input circuit to the capacitors.

Light Source

The light source for this system is the H6 mercury-vapor lamp (ref. 4). The lamp requires a minimum of about 1300 volts to start (1600 volts direct current) and will operate at alternating current between 600 and 2000 volts. For schlieren photography the water-cooled A-H6 lamp is used in this system to minimize extraneous distortions produced by heated-air currents.

The glass water jacket was replaced by an opaque jacket of equal length (3.625 inches (92.08 mm)) and outside diameter (1 inch (25.40 mm)) made of bakelite (fig. 7). The water passages through the interior of the bakelite jacket duplicated those of the glass jacket. A light exit was provided by drilling a 0.07-inch (1.78-mm) hole radially into the jacket approximately midway along the length of the narrow (0.375-inch (9.52-mm) diameter) part of the water passage. This hole was then counterbored to a depth of 0.20 inch

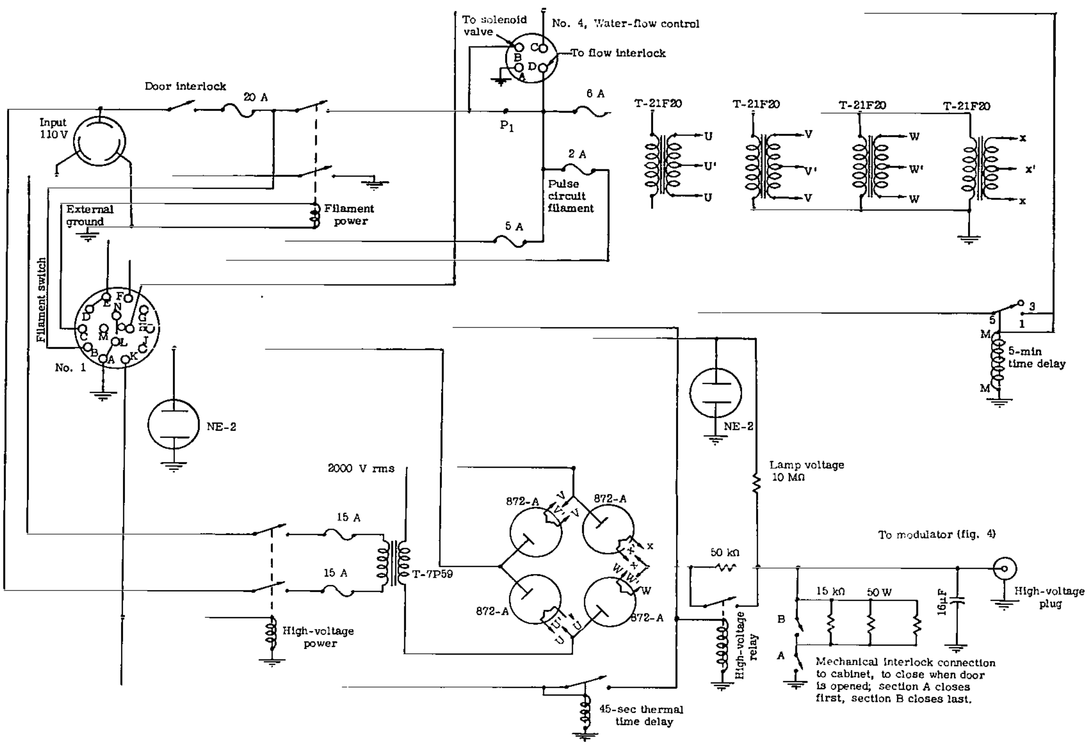


Figure 6.- High-voltage power-supply unit.

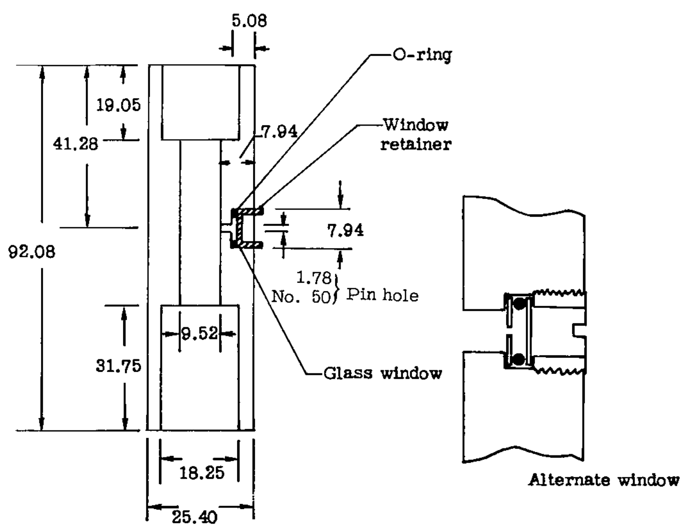


Figure 7.- Mercury-vapor-lamp water jacket and light window. All dimensions are in millimeters.

(5.08 mm), leaving a wall thickness of 0.11 inch (2.79 mm), to permit the installation of an 0-ring, a thin glass window, and a 0.3125-inch-diameter (7.94-mm-diameter) threaded tube to hold the glass window in place and provide a seal. This jacket and an alternate window design are shown in figure 7. The light or luminous flux was measured in front and behind the knife edge. These measurements were used to set the knife edge for a 50-percent blockage position and to adjust the capacitance for proper exposure of film.

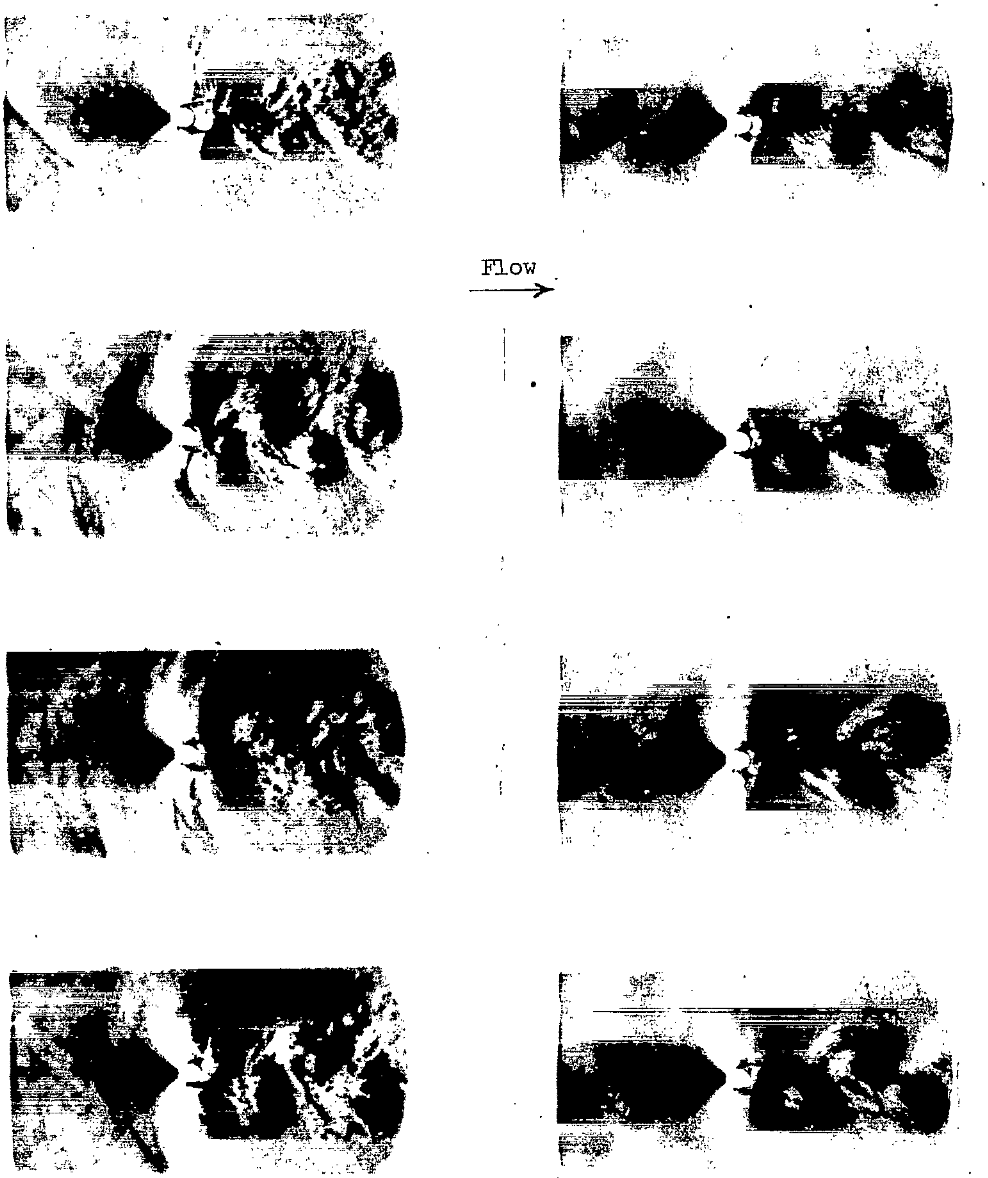
In the operation of this lamp a cooling problem was encountered and solved. The public water supply was used initially for cooling the lamp. The minerals in the water were deposited around the electrical terminals of the lamp and caused malfunctioning. To remedy this, a closed-circuit cooling system was developed that pumped distilled, deionized water from a reservoir through the water jacket and back to the reservoir. The water in the reservoir was cooled by a coil through which the public water flowed. No mineral deposits were encountered with this system.

RESULTS AND DISCUSSION

General Characteristics

Schlieren photographs of the flows past models have been obtained by using a continuous-light source and a 16-mm high-speed camera operating at frame rates from 2000 to 7000 per second. These photographs showed that the flow at 2000 frames per second (exposure 170 μsec) was very indistinct while at 7000 frames per second (exposure 50 μsec) the flow was fairly well defined. Photographs obtained by using the synchronized flashing light (exposure 4 μsec) at 300 frames per second provided more sharply defined flows than those obtained with the continuous-light source at 7000 frames per second as shown in figure 8. Photographs of the flow past airfoils obtained by using the flashing-light technique at several frame rates are shown in figure 9. The system operated reliably up to 760 frames per second. At higher frame rates erratic performance was encountered. The erratic performance and its solution are discussed subsequently.

Aerodynamic research prior to the publication of reference 3 had indicated that the motions of the flows encountered often have an overall cyclic character such that, even though their frequencies may vary in somewhat random fashion, the nature of the motion can usually be adequately defined when a large number of exposures is obtained with moderate time intervals between exposures. The minimum framing rate of the 16-mm high-speed camera used with the flashing-light system was 300 frames per second. Subsequent investigations, for example references 5 to 8, demonstrated that framing rates around 10 per second were generally sufficient for analysis of flows as illustrated by figure 10. Furthermore the lower frame rate was readily adapted to 35-mm-camera operation and the 35-mm-film format was of adequate size for use in all forms of publications and presentations. For some work higher frame rates can be needed.



Flashing light
300 frames per second
exposure 4 μsec

Continuous light
7000 frames per second
exposure 70 μsec

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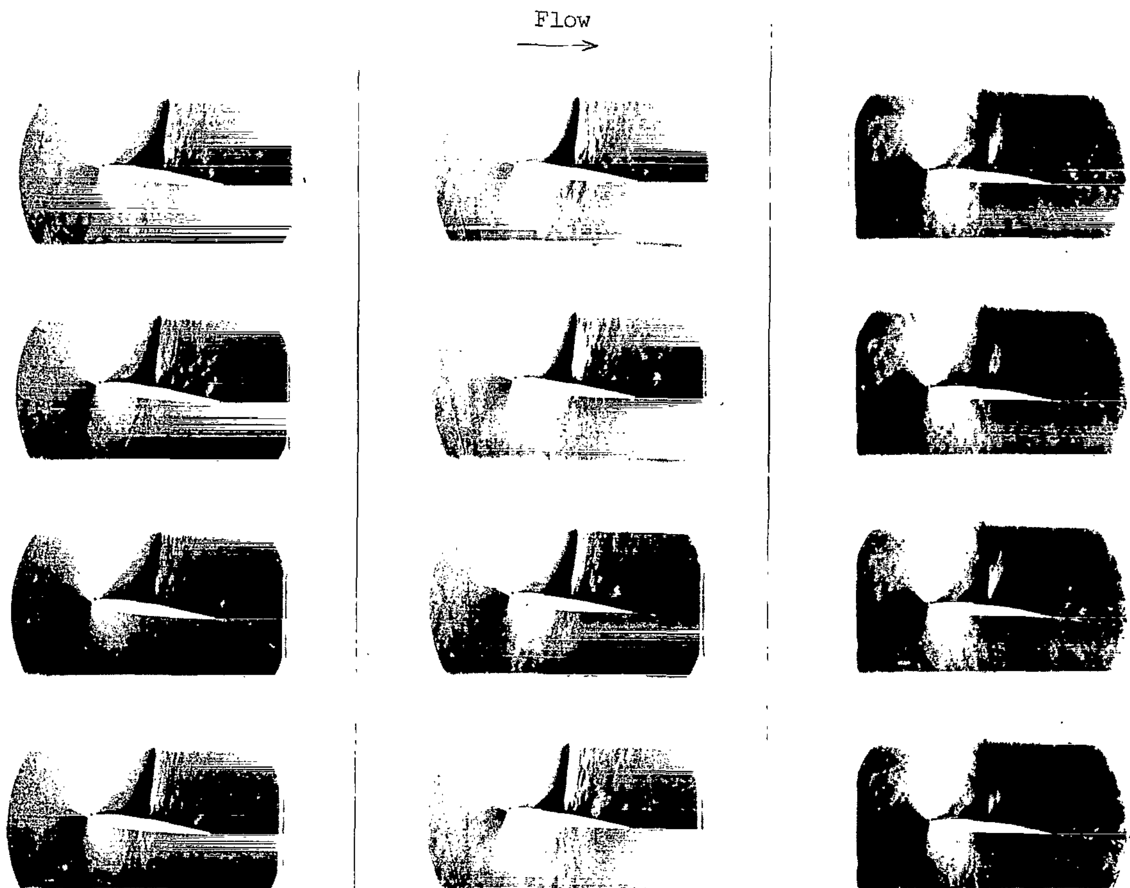
Figure 8.- Comparison of photographs from two techniques.



460 frames per second | 760 frames per second | 2160 frames per second

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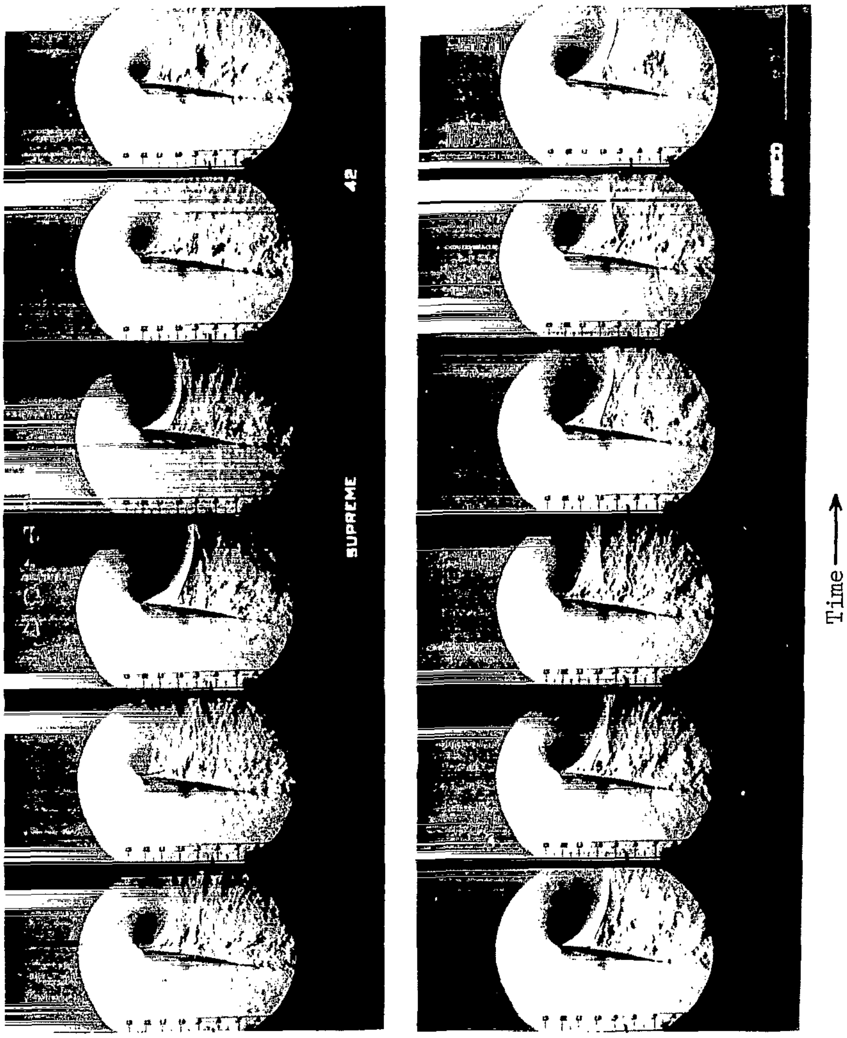
Figure 9.- Flow past airfoil photographed by flashing-light technique.

The present system as presented in figures 2 to 6 was not modified to improve performance at high frame rates, that is greater than 750 frames per second. The system performance and limitation at high speeds is the same as that of the initial system described in reference 3. Reliable operation of the equipment was obtained with the 35-mm camera at low frame rates and with the 16-mm high-speed camera from its lowest operational speed of 300 frames per second up to 750 frames per second. At frame rates in excess of 750 per second, unsatisfactory operation was encountered. The unsatisfactory operation consisted of skipping frames and was of two types: Alternate pictures and blanks, or long blanks followed by short bursts of photographs. As an illustration of the combination, at 2160 frames per second a blank strip of about 150 frames was followed by a strip of 40 consecutive pictures (a part of which is shown in fig. 9) followed by a strip of alternating one blank and one picture. This erratic behavior was repeated (not cyclic) within the 100-foot (30.48-meter) strip. The fact that 40 consecutive pictures were obtained at 2160 frames per second is an indication that with further



Beginning of oscillations $M \approx 0.825$ | Near end of oscillations $M \approx 0.845$

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Figure 10.- Oscillatory flow.

development satisfactory operation at frame rates approaching 2000 could be obtained with this system if needed. A reduction in the capacitance of the power capacitor from 0.2 to 0.1 μF permitted operation at film speeds of the order of 1500 frames per second but the light intensity was too low to provide acceptable photographs when the desired 50-percent cutoff at the knife edge was retained.

An analysis of the flashing-light system and its observed performance has been made to determine the required changes in the system to obtain properly exposed film at frame rates in excess of 1000 per second. The analysis involves the electrical behavior of the charging circuit and the general operating characteristics of the mercury-vapor lamp.

During the charging cycle the rate of change of voltage on the capacitors is

$$\frac{dv}{dt} = \frac{E_0}{RC}\epsilon^{-\frac{t}{RC}} \tag{1}$$

The capacitor voltage immediately prior to discharge or at the instant the thyratron triggers is

$$e = E_0 - \left(E_0 - E_3\right)\epsilon^{-\frac{1}{nRC}} \text{ volts} \tag{2}$$

However $E_3 \approx 0$; thus

$$e = E_0\left(1 - \epsilon^{-\frac{1}{nRC}}\right) \text{ volts} \tag{3}$$

The average power input to the lamp is

$$P = \frac{1}{2} Ce^2 n \text{ watts} \tag{4}$$

where e is the voltage immediately prior to flashing and n is the flashing rate.

The energy input to the lamp per flash from equation (4) is

$$\frac{P}{n} = \frac{1}{2} Ce^2 \text{ watt-seconds} \tag{5}$$

The voltage E_0 is fixed by the transformer and rectification circuit of the high-voltage power supply (fig. 6) and the input voltage. The product nRC is the controlling factor, and as it increases, the capacitor voltage e decreases exponentially.

The H6 lamp is rated for an average power input of 1000 watts or in equation (4) $P \leqq 1000$. In flashing operation the energy input per flash P/n (eq. (5)) should not exceed 4 watt-seconds because the lamp can explode at an input of 8 watt-seconds per flash. The lamp normally operates at 840 volts, but the voltage required initially to start the lamp E_1 is around 1300 volts root mean square (1600 volts on direct current). On 60-cycle alternating current the lamp can operate down to a voltage of about 600 with a flashing rate of 120 per second. If the flashing rate is continuously decreased, a value will be reached at which the lamp will cease to flash at the low voltage and the voltage will have to be increased to a value approximating the starting voltage E_1 to resume functioning. The manufacturer of the lamp states that, at the removal of the current, complete deionization occurs within 1 to 10 milliseconds.

If R and C are fixed at values that produce satisfactory photographs on each frame at frame rates n from 300 to 750 per second and if n is increased, the voltage e decreases as indicated by equation (3) and observed on an oscilloscope. When n is increased beyond 1000 frames per second, e for the succeeding frame drops below E_2, the minimum voltage required for steady operation, and the lamp fails to flash. One or more frames will be skipped (will be blank) until the voltage on the power capacitors at the instant the thyratron is triggered e is equal to or in excess of the voltage required to flash the lamp. The voltage required to flash the lamp is E_2 if the lapsed time (charging time) t is less than about 8 milliseconds. If the lapsed time is greater than about 20 milliseconds, the voltage required to flash will be about E_1. The absolute voltages and consequently the lapsed time can be affected by the particular H6 lamp and its condition, especially the mercury distribution within the lamp.

Consider the operation observed with reduced capacitance. When n was doubled (from 750 to 1500) and C halved (0.2 to 0.1 μF), the product nRC is constant. The voltage e (eq. (3)) is not affected and the lamp flashes without skipping frames. The energy input per flash however is halved (eq. (5)) and results in insufficient light intensity for proper exposure as observed.

There is no positive explanation for the performance of long blanks followed by short bursts and then alternate frames. The characteristics of the charging circuit previously discussed combined with an erratic response of a lamp that is on the verge of failing to respond to the potentials provided e might be the answer. Generally, however, consistent flashing of a lamp is dependent primarily on the value of e at a time $t = \frac{1}{n}$ for each frame. Adequate light output is dependent on the energy input per flash and therefore on e and C (eq. (5)). Thus when n is increased twofold from 750 to 1500 frames or flashes per second, the charging circuit resistance R should be decreased to about one-half of its initial value to increase the charging rate (eq. (1)) and retain the capacitor potential e (eq. (3)) and thus the power per flash (eq. (5)).

Although performance tests of the system with the high-speed camera at reduced values of charging resistance have not been conducted, the tests have been simulated without evaluating the exposure. The 16-mm-camera input was connected to an audio oscillator and the capacitor voltage and its variations with time were observed on an oscilloscope. These observations confirm the analysis and indicate that with a 40-percent reduction in the charging circuit resistor R_l consistent flashing rates approaching 1500 per second with $C = 0.2\ \mu F$ can be obtained. At 1500 frames per second the flashing alternated between 750 frames and 1500 flashes per second. At 1400 frames per second the flashing was consistent at 1400 per second. These oscilloscope tests also showed that if the charging resistance is reduced to too low a value, the charging circuit is capable of changing the lighting mode from flashing to continuous. The continuous mode could be prohibited by incorporating a switching device in the charging circuit with control circuitry that electrically disconnected the high-voltage power supply from the power capacitors during the discharge of the capacitors through the lamp. This feature allows further decrease in the charging resistor R_l and a consequent increase in usable framing rate of the camera and equipment.

When ultra-high-speed frame rates (above 50 000) are required, a different approach is utilized. A system described in reference 9 provides framing rates of 75 000, 300 000, and 1 200 000 per second for a total film length of 72 frames. An ultra-high-speed framing camera is used in a continuous-light mode. The light is produced by a pulsed xenon lamp having a total pulse duration tailored to the frame rate to avoid double exposure of any frame. The exposure time 1/3n is 4.45 microseconds for 75 000 frames per second.

An Extended Application – The Duplex Schlieren System

The flashing light synchronized with the framing of motion-picture cameras for use in recording schlieren photographs as described herein has been developed with modifications or alterations being made following an operational or analysis need. The light-camera feature in combination with a schlieren system having components of high optical quality and arranged in precision alinement (see appendix) have produced highly satisfactory photographs in transonic, supersonic, and hypersonic aerodynamic research. Operationally, however, another feature is needed or required.

In the operation of hypersonic and supersonic wind tunnels and especially for blowdown tunnels it is very desirable for the operator to have continuous monitoring of the test flow throughout the test run. This information will enable the operator to see that the desired hypersonic or supersonic flow has been established before starting to record test data and to see that the flow is maintained throughout the recording of the test data. In all speed ranges a monitoring channel can be beneficial to the operator to observe the flow changes that occur with change of model attitude or Mach number.

Accordingly a duplex system, which is a two-channel schlieren optical system, was developed. Each channel of this system can be operated independently of the other. The first channel is used for data recording while the second channel is used for visual monitoring at will. The system has a dual purpose: First, it must provide high quality schlieren photographs for analysis and data; second, it must provide the operator with visual observations of the test conditions before, during, and after recording the test data.

The first requirement is satisfied in the first channel by using the flashing light synchronized with camera as discussed previously and constitutes the recording system. Compromises in this recording system, which is the primary system, are avoided by setting up the recording system as in figure 11 as carefully as possible (see alinement in appendix) and then adding or installing a secondary system without disturbing any element of the primary system as shown in figure 12. A continuous-light source, a secondary source, is installed in the on-axis plane at a distance f_1 from the collimating mirror

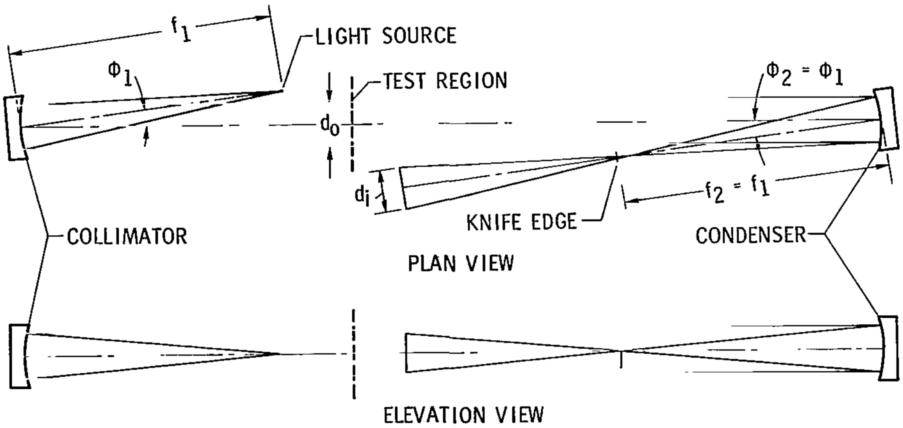

Figure 11.- Schematic of schlieren system using mirrors in an off-axis arrangement.

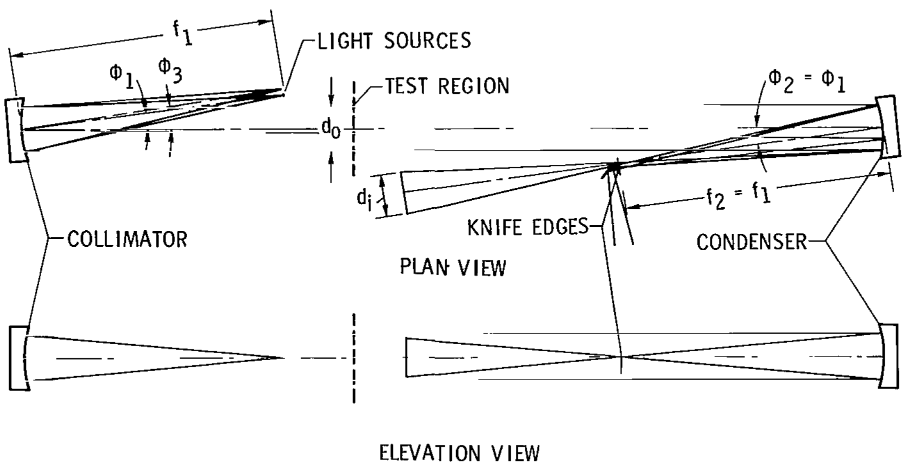

Figure 12.- Schematic of duplex schlieren system.

(see appendix and compare figs. 11 and 12) and form an angle ϕ_3 from the mirror axis. The angle ϕ_3 is somewhat greater than ϕ_1 and the spacing between the primary and secondary light sources s is kept to a small value. The spacing is reduced by using a small front surface mirror to fold the path of the secondary light source as shown in figure 13. These light sources are a part of a duplex system having F/7 mirrors of 13.5-inch (0.343 m) clear aperture. The effective light-source spacing s in figure 13 is 0.65 inch (0.016 m).

The image of the secondary light source is formed in the on-axis plane by the condenser at an angle approximately equal to ϕ_3 from the mirror axis and displaced from the primary light-source image by a distance approximately equal to s. Into this image

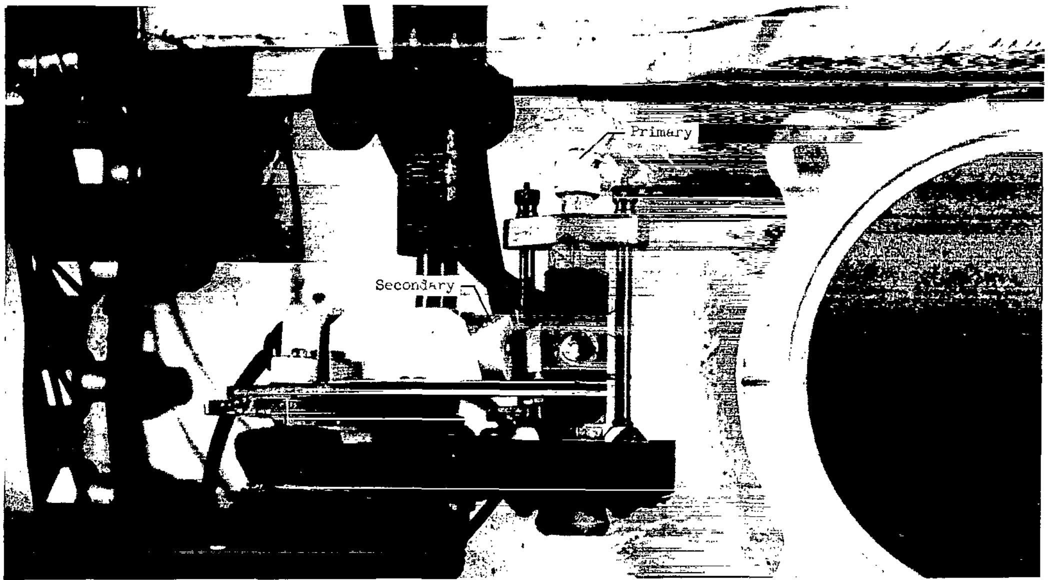

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Figure 13.- Primary and secondary light sources.

of the secondary light source an independent knife edge (the secondary knife edge) is inserted with independent adjustments along three mutually perpendicular axes and rotation about the optical axis. The complete knife-edge assembly is shown schematically in figure 14. The secondary knife edge is adjusted without disturbing the adjustment of the primary knife edge, and the 50 percent of secondary light passing this secondary knife edge is reflected by a ball-and-socket-mounted front surface mirror onto a screen, by using suitable optics for focusing and directing, or into a closed-circuit television camera. The screen or television monitor is then used for observing the flow independently of the primary or recording system.

The optical stops in both channels of the schlieren system are the clear apertures of the mirrors and the windows at the test region. For the primary or recording channel, the minimum diameter of these optical stops determines the field diameter d_o. For the secondary or visual channel the schlieren image has the shape of the arcs of two circles, the centers of which are displaced in the on-axis plane. The displacement of the two arcs when the mirrors alone are the optical stops is

$$\text{Displacement} = \frac{sm}{f}$$

where m is the axial distance from mirror to mirror or length of mirror axis. The actual physical separation of the two light sources has some minimum usable

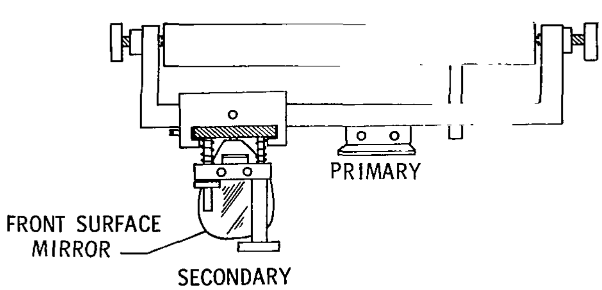


Figure 14.- Schematic of duplex knife edges.

value. This value is determined either by the physical sizes of the housings of the light sources (fig. 13) or by the least usable separation of the two knife edges with the reflecting mirror behind the secondary knife edge (fig. 14).

The quality of the schlieren image produced by the secondary system is degraded somewhat but is quite adequate for visual observations or monitoring. The quality of the schlieren image in the primary system is not compromised in any manner. The duplex schlieren system composed of the two separate and independent channels and incorporating the synchronized flashing light in the primary channel has proven in operation to be highly satisfactory and quite flexible. The secondary system as described can be adapted to almost any primary system provided the displacement sm/f is not too large.

Other Applications

In the application of the flashing light synchronized with the framing of motion-picture cameras in schlieren photography it was necessary to restrict the light to a small effective source (see appendix) as shown in figure 7. Thus only a small part of the total light available from the basic lamp (maximum input of 4 watt-seconds per flash) was used. The combination of 4-microsecond flashes (exposure time) combined with framing rates from 10 to about 1400 per second is applicable to other studies of rapid motions such as are encountered in material processing, machinery, and the like. For many applications the total light output of this 1000-watt lamp would provide sufficient illumination. Additional light can be provided, if needed, by duplicating a part of the modulator and providing additional capacitors and thyratron to operate the additional lamp. The basic circuit is believed to be adequate to operate several thyratron tubes and therefore serve several lamps operating simultaneously.

The water-cooled A-H6 lamp was used in schlieren photography because the jacket was adaptable to masking without affecting operation and water cooling minimized the problems associated with heated-air currents. In other applications the air-cooled B-H6 lamp could be more applicable because it is more easily installed and the cooling problem is simpler. Any H6 lamp will function with the electronic system described herein.

CONCLUDING REMARKS

A photographic system has been developed and operated wherein a 1000-watt mercury-vapor lamp is flashed in synchronization with the framing of 16-millimeter high-speed and 35-millimeter low-speed cameras. The flash of light has a duration of about 4 microseconds and is triggered either by a generated sinusoidal voltage at high speeds or by a make-break switch at low speeds. The system is capable of flashing at rates from below 10 to about 1400 per second.

This recording system was developed and operated in schlieren photography of flows in aerodynamic research. This schlieren system has been expanded by the addition of an independent channel that permits visual monitoring of the test conditions at will and independent of the recording system.

The light, controls, and camera of the recording system are applicable to other studies involving rapid motion such as those encountered in processing and in machinery.

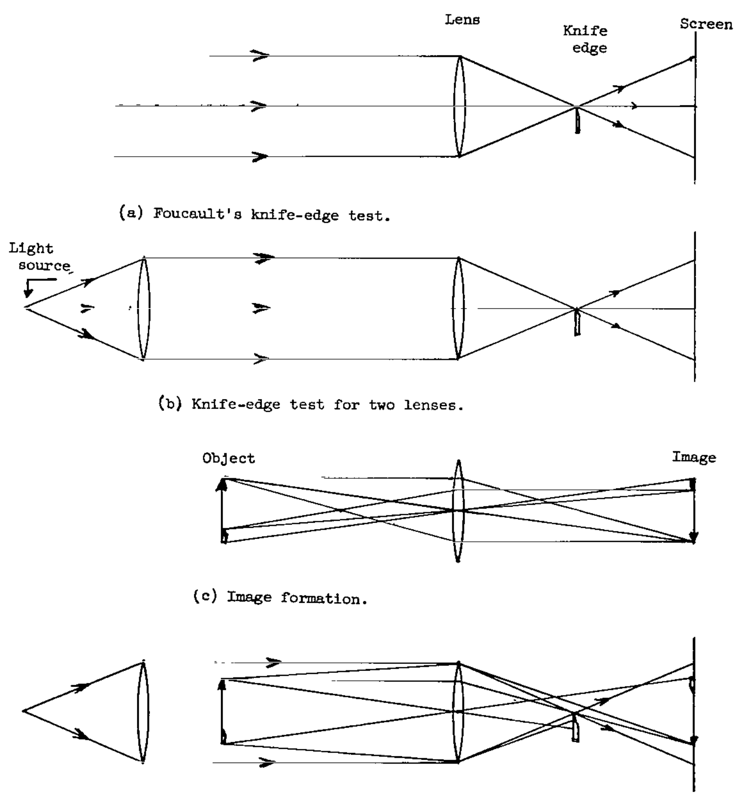
Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., March 26, 1970.

APPENDIX

SCHLIEREN

Principles

The schlieren method of visualizing refractive deviations of light was proposed by A. Toepler as a new optical method and named the "schlieren method" a few years after Leon Foucault, in 1859, published his development of the knife-edge test. Foucault's knife-edge test provided an excellent method of testing the ability of a telescope objective to focus all light rays from a star into a single-point image. This test also gives visual indication of those parts of the objective that require additional figuring as well as the extent of the error. As the knife edge is moved gradually into the image at the principal focus, portions of the objective, the focal lengths of which differ, appear with variations in brightness in the image of the objective. Figure 15(a) is a sketch of the Foucault knife-edge test of a corrected lens. One corrected objective lens can serve as a collimator to convert light from a point source into a column of parallel light rays so that a second lens can be tested in the laboratory as in figure 15(b). This figure shows most of the basic



(a) Foucault's knife-edge test.

(b) Knife-edge test for two lenses.

(c) Image formation.

(d) Schlieren system.

Figure 15.- Development of schlieren system.

elements of a schlieren system: light source, collimator, condenser, knife edge, and screen. However, one additional function of the condenser must be considered. This function is the ability of the condenser to form an image of an object. All light rays emanating from a point in the object that fall upon the condenser are converged to reform the corresponding point in the image plane (fig. 15(c)). The complete schlieren system in figure 15(d) is a combination of figures 15(b) and 15(c) wherein the object becomes the test region and the image is the observation screen or film plane.

The functioning of the knife edge and its effect on light rays that undergo angular deviation or refraction in the test region is illustrated in figure 16. Upward refractions pass over the knife edge and produce an increase in brightness in the corresponding image position on the screen. Downward refractions are blocked by the knife edge and result in decreased brightness in the image. For equal response in both directions the knife edge must be positioned for a 50-percent blockage of the light-source image. The angular deviation of the light rays in the test region ω produced by a mass-density gradient $d\rho/dx$ in the same plane and of depth y along the optical axis is given by Fermat's theorem expressed as

$$\omega = \frac{60.6y}{\rho_o + 0.000294\rho} \frac{d\rho}{dx} \text{ arc seconds}$$

Alinement

When lenses are used as collimator and condenser as in figure 16, all elements must be alined on axis. However paraboloidal mirrors of high optical quality are free of chromatic aberrations, more readily available, and more economical than lenses of comparable quality. Paraboloidal mirrors therefore are generally used in schlieren systems and are installed off axis as shown in figure 11 to provide an unobstructed view of the test region. The components of the system are identified in figure 11. A light source is

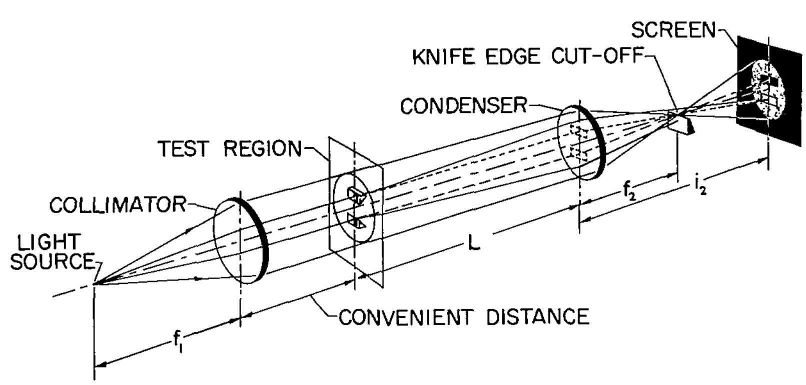


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Figure 16.- Illustration of functioning of schlieren system.

located at the focus of a collimator; this produces a column of approximately parallel light that passes through the test region and onto the condenser. The condenser forms an image of the light source in its focal plane. A knife edge positioned in the light-source image intercepts or blocks half of the light. The remaining light diverges onto a screen or film plane which is the location of the image of the test region as formed by the condenser alone or in combination with auxiliary lenses that are located behind the knife edge toward the screen. In alining this off-axis schlieren system, two views must be considered simultaneously. The views are in planes passing through the axis joining the two mirrors (mirror axis) and at right angles to each other. In one plane (plan view in fig. 11) the light source is displaced from the mirror axis by an angle ϕ_1 which is held to a minimum practical value to minimize aberrations. The condenser is adjusted so that the light-source image is displaced from the mirror axis by an angle ϕ_2 equal and opposite to ϕ_1 to cancel some of the off-axis aberrations introduced at the collimator. The cancellation and alinement procedures are benefited when the focal lengths of the collimator and condenser are approximately equal; that is $f_1 = f_2$. (See also refs. 10 to 13.) In the other plane, elevation view in figure 11, all components including the edge of the knife edge are on axis as shown. Some aberration effects occur, as evidenced by unequal light distribution on the screen, if the light source and its image are above or below this on-axis plane by as little as 1 percent of the focal length. In some cases when ϕ_1 is near its maximum value, unequal light distribution is observed when the knife edge is rotated 90^o from an in-the-plane to a perpendicular-to-the-plane position. (Note that the locations for the knife edge in the two orientations are different as indicated in fig. 11.) The aberration effects as well as alinement difficulties are more noticeable with the small focal length-to-diameter ratios of about F/5.

The column of light passing through the test region should be slightly divergent (illuminated disk at condenser slightly larger than clear aperture of collimator with no obstruction or masking between the mirrors as at test region). The slight divergence assists in minimizing or avoiding model surface reflections that can arise in part from the finite size of the light source.

Sensitivity

The angular deviations of the light in the test region ω produced by a gradient in mass density $d\rho/dx$ is given by Fermat's theorem as

$$\omega = \frac{60.6y}{\rho_o + 0.000294\rho} \frac{d\rho}{dx} \text{ arc seconds} \tag{A1}$$

The resulting change in illuminance of the schlieren image on the screen or film plane $\Delta\beta$ in terms of the basic or background illuminance β for alinements in which the knife edge is positioned to block 50 percent of the undeviated source image is

$$\frac{\Delta\beta}{\beta} = \frac{1}{103}\frac{f\omega}{h} \tag{A2}$$

The least detectable angular deviation of light ω_{min} is a measure of the sensitivity of the system and corresponds to the least detectable relative change in illuminance $\left(\frac{\Delta\beta}{\beta}\right)_{min}$ or

$$\omega_{min} = 103\left(\frac{\Delta\beta}{\beta}\right)_{min}\frac{h}{f} \text{ arc seconds} \tag{A3}$$

The maximum detectable angular deviation ω_{max} corresponding to a detectable $\Delta\beta/\Delta\omega$ occurs when the displacement at the knife edge approaches $\pm\frac{h}{2}$ or $\frac{\Delta\beta}{\beta} = \pm 1$. Thus equation (A2) becomes

$$\omega_{max} = 103\frac{h}{f} \text{ arc seconds} \tag{A4}$$

For angular deviations greater than ω_{max} the illuminance remains constant (provided $\omega > \omega_{max}$ does not exceed the optical stops of the system). Equation (A4) represents an absolute maximum at which the illuminance in the schlieren image attains a maximum value or zero (total darkness). The detectable value of $\left(\frac{\Delta\beta}{\beta}\right)_{max}$ should be less than 1.

The value of $\left(\frac{\Delta\beta}{\beta}\right)_{min}$ in equation (A3) is difficult to evaluate analytically. The term $\frac{f\omega_{min}}{h}$ $\left(\text{equal to } 103\left(\frac{d\beta}{\beta}\right)_{min}\right)$ has been experimentally determined for paraboloidal mirrors having focal length-to-diameter ratios (F numbers) of 5, 7.2, and 8.4 installed accurately in an off-axis schlieren system as in figure 11 with $f_1 = f_2$ and $\phi_1 = \phi_2$. Light deviations in the test section were produced by calibrated glass wedges arranged in pairs having positive and negative refractions. The range of deviations was from ±1 to ±60 arc seconds. The light sources used were of two types: The circular sources had diameters of 30 mils (0.76 mm) and 60 mils (1.52 mm), and rectangular tungsten filaments having a wide variety of width-to-height ratios with lengths from 122 mils (3.10 mm) to 620 mils (15.75 mm) were used. In one case, F/7.2, a light source of 3-mil (0.08-mm) diameter with high intrinsic brightness was used but the schlieren image was too dim to evaluate sensitivity adequately (table II). Some additional tests were made to determine the effect of off-axis angle ϕ_1 and to examine the performance of a circular orifice as a knife edge. The results obtained are summarized as follows:

APPENDIX

$\phi_1 = \phi_2 \leqq 9.2^o$	
$\frac{w}{h}$	$\frac{f\omega_{min}}{h}$
0.01	7
.06	7
.08	7
[a]1.00	6
12.00	20
17.40	40
103.00	60

[a]Circular.

[a]$\frac{w}{h} = 1$	
$\phi_1 = \phi_2$, deg	$\frac{f\omega_{min}}{h}$
5.5	6
7.9	7
9.2	7
11.6	7
12.0	[b]8.4

[a]Circular.

[b]Accompanied by nonuniform light distribution for F/5 and $\frac{h}{d_m} = 3.0$, but for $\frac{h}{d_m} = 6.0$, the distribution was approximately uniform.

Circular orifice for knife edge	
$\frac{\text{Source size, } h}{\text{Orifice diameter}}$	$\frac{f\omega_{min}}{h}$
1	90
.75	108
.50	144

Some limited tests with circular light sources indicated that equation (A4) should be decreased to about

$$\omega_{max} = 60 \frac{h}{f} \text{ arc seconds} \tag{A5}$$

Also these tests indicated that for circular light sources and for $\frac{w}{h} \leqq 1$

$$\omega_{min} = 6 \frac{h}{f} \text{ arc seconds} \tag{A6}$$

Analyses of the factors affecting the sensitivity of schlieren systems are usually based upon geometric optics and evaluate the idealized image of the light source. This ideal image is of uniform brightness and is without variations in aberration effects throughout its area of width and height. These analyses derive relations such as expressed in equations (A2) and (A4) and provide an additional conclusion for elliptical and rectangular-shaped images that the width along the knife edge w has no effect on the sensitivity (for example, see ref. 13). Consequently there is a widespread practice to use light sources having moderate to large width-height ratios. The user concludes from these analyses that the sensitivity of this system is high based on a small value of h/f and that the illumination β is ample based on $h \times w$.

When an analysis of the effects of light-source width is started at the source, the validity of the previous assumptions pertaining to the image of the source become questionable. Consider three points on a line source of height h and width w, one on axis and the remaining two at either end of the line in question. The central point produces a column of light that is alined on axis with the condenser as in figure 11. The two points at the ends produce columns that diverge from the mirror axis (and from each other) and overlap the edges of the condenser, as shown by one point in figure 12, and result in decreased light intensity at the ends of the source image. These two end points are also in a misalined condition and can degrade the quality of the system as discussed in the duplex system for the secondary channel. These effects are small but a sensitive schlieren system is quite capable of detecting very small deviations. See table II. The evaluation of the effects of the height-width ratios of light sources by actual application and study in a sensitive schlieren system $(\omega_{min} = 2 \text{ seconds})$ evaluates all factors and consequently provides the most credible answers.

Several conclusions are indicated by these experimental results. As the width-to-height ratio of a light source is increased beyond unity, a given system (h and f constant) is degraded in maximum sensitivity (least value of ω_{min}) and in range $(\omega_{max} - \omega_{min})$. The optimum light source is one with a width-to-height ratio of about unity. The off-axis angle ϕ_1 should not exceed 11°.

APPENDIX

Auxiliary Lens

There are a few cases in schlieren photography where the condenser alone forms the final image of the test region. For these cases the image distance from the condenser i_2 and the image size of the test region d_i can be derived from the thin-lens formula and are

$$i_2 = \frac{f_2 L}{L - f_2} \tag{A7}$$

and

$$d_i = \frac{f_2 d_o}{L - f_2} \tag{A8}$$

In most systems, as in the flashing light with its camera as well as in the secondary channel of the duplex system, auxiliary lenses are used and it becomes necessary to determine the lens aperture d_c, focal length f_3, and position a of this lens to bring to focus the test region on and to cover a given format of film. In situations where the illuminance from the desired light source is inadequate to provide proper exposure of the film, a reduction in the size of the schlieren image provides a solution. The film location b and the schlieren image size d_i are derived by starting with equation (A7), which gives the object location for the auxiliary or camera lens (object distance is $i_2 - f_2 - a$ in fig. 17), and employing the thin-lens formula. By using the symbols and designations in figure 17 the resulting relations are

$$b = f_3 \frac{f_2(f_2 + a) - La}{f_2(f_2 + a - f_3) - L(a - f_3)} \tag{A9}$$

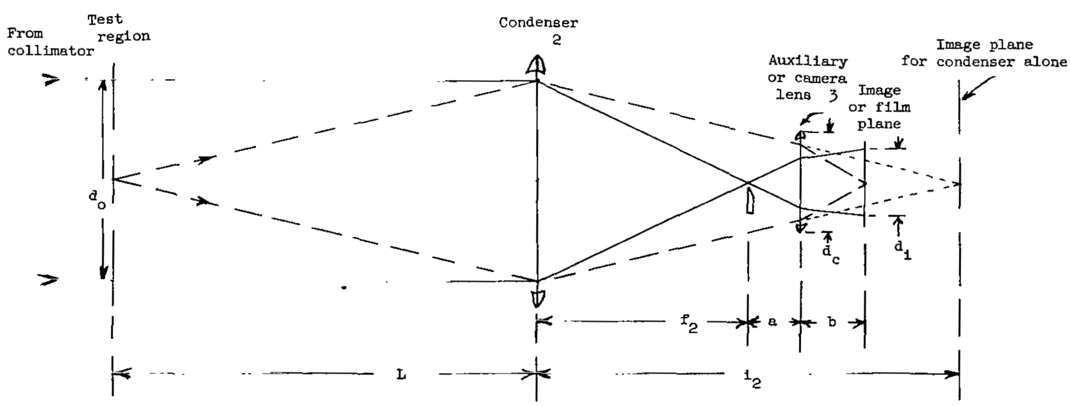

Figure 17.- Auxiliary-lens installation.

$$\frac{d_i}{d_o} = \frac{f_3 f_2}{f_2(f_2 + a - f_3) - L(a - f_3)} \tag{A10}$$

To accept all undeviated light passing the knife edge, the clear aperture of the auxiliary or camera lens d_c as derived from figure 17 is

$$d_c = d_o \frac{a}{f_2} \tag{A11}$$

However to collect the deviated light and reduce alinement problems

$$d_c > d_o \frac{a}{f_2} \tag{A12}$$

The amount of increase is dependent on the clear apertures of all lens elements in the assembly of the camera lens, the rear elements of which can cause vignetting of the image.

In the usual setup b is less than f_3 and requires cameras to have a focal position beyond infinity or the lens assembly needs to be moved closer to the film plane than in normal operation. Alterations to the camera can be avoided by attaching a negative spectacle lens as in a filter holder in front of the camera lens. The power of the supplementary lens expressed in diopters will depend on the particular combination of f_2, f_3, and a; values generally fall in the range from -0.5 to -2.5.

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TABLE I.- CONNECTIONS TO PLUG-IN UNITS

Control unit	High-voltage power supply
14-terminal plug no. 1	
A_1 and L_1 and ground	A_1 and L_1 and ground
B_1 to filament switch and to C_1	B_1 from 110-Vac power and through door interlock and 20-A fuse
C_1 from B_1 through filament switch	C_1 to filament power relay coil and to ground
D_1 to E_1	D_1 to E_1 (for pulse-amplier power)
E_1 and D_1 to C_2 and mode-selector switch	E_1 from 110-Vac power at P_1 through 5-A fuse (amplifier power)
F_1 to B_3	F_1 from 110-Vac power at P_1 through 2-A fuse (modulator power)
G_1 to { ① high-voltage switch to K_1; ② high-voltage ready lamp and to ground }	G_1 from P_1 through $D_4 \rightarrow C_4$ and 5-min time-delay relay
H_1 to high-voltage-on lamp and to ground	H_1 from K_1 through 45-sec thermal time delay
J_1 to lamp-current meter and to ground	J_1 from rectifier anode output
K_1 from G_1 through high-voltage switch	K_1 to { ① high-voltage power-relay coil to ground; ② 45-sec thermal time-delay contact, and coil to ground; ③ H_1 and high-voltage relay through ② and thermal time delay }
L_1 to A_1 and ground	L_1 from A_1 and ground
M_1	M_1
N_1 to lamp-voltage meter to ground	N_1 from rectifier cathode through 10-MΩ resistor
O_1 to coolant-on lamp to ground	O_1 from C_4
Three-terminal plug no. 2 for pulse amplifier	Four-terminal plug no. 4 for water-flow control
A_2 to ground	A_4 to ground
B_2 from mode-selector switch for alinement	B_4 from 110-Vac power at P_1
C_2 from D_1 and E_1, and to mode-selector switch	C_4 to O_1, and 5-min time-delay contact and coil to ground
Two-terminal plug no. 3 for modulator	D_4 from 110-Vac power at P_1
A_3 to ground	
B_3 from F_1	

TABLE II.- SENSITIVITY MEASUREMENTS

$\left[d_o = 10 \text{ in. } (0.254 \text{ m}); \ \frac{d_i}{d_o} = 1.0\right]$

F	ϕ	$\frac{w}{d_o}$	$\frac{h}{d_o}$	ω_{min}	$\Delta\omega_{min}$	$\frac{w}{h}$	$\frac{f\omega_{min}}{h}$
5.0	9.2	[a]3.0	[a]3.0	3.5	±0.5	1	5.8
7.2	6.4	[a]3.0	[a]3.0	2.5	±.5	1	6.0
8.4	5.5	[a]3.0	[a]3.0	2.0	---	1	5.6
5.0	9.2	[a]6.0	[a]6.0	7	---	1	5.8
7.2	6.4	[a]6.0	[a]6.0	5	---	1	6.0
8.4	5.5	[a]6.0	[a]6.0	4	---	1	5.6
5.0	9.2	12.2	.7	5	---	17.4	35.8
5.0	9.2	20.5	1.7	6	---	12.0	17.5
5.0	9.2	[a]6.0	[a]6.0	7	---	1	5.8
5.0	9.2	[a]3.0	[a]3.0	3.5	±.5	1	5.8
7.2	6.4	62.0	.6	5	±1.0	103	60.0
7.2	6.4	12.2	.7	4	±1.0	17.4	46.3
7.2	6.4	20.5	1.7	5.5	±1.5	12.0	23.3
7.2	6.4	[a]6.0	[a]6.0	5	±0	1	6.0
7.2	6.4	[a]3.0	[a]3.0	2.5	±.5	1	6.0
[b]7.2	6.4	[a].3	[a].3	4	---	1	96
7.2	6.4	[a]3.0	[a]3.0	2.5	±.5	1	6.0
7.2	6.4	[a]6.0	[a]6.0	5	±0	1	6.0
7.2	6.4	1.7	20.5	20	±2.0	.08	7.0
7.2	6.4	.7	12.2	12	---	.06	7.1
[c]7.2	6.4	.6	62.0	55	±5.0	.01	6.4
5.0	9.2	[a]3.0	[a]3.0	3.5	±.5	1	5.8
5.0	11.5	[a]3.0	[a]3.0	4	---	1	6.7
[d]5.0	12.7	[a]3.0	[a]3.0	5	---	1	8.3
5.0	9.2	[a]6.0	[a]6.0	7	---	1	5.8
5.0	12.5	[a]6.0	6.0	8	---	1	6.7
8.4	5.5	[a]3.0	[a]3.0	2	---	1	5.6
8.4	7.9	[a]3.0	[a]3.0	3	---	1	8.4
8.4	12.0	[a]3.0	[a]3.0	3	---	1	8.4
8.4	5.5	[a]6.0	[a]6.0	4	---	-----	5.6
8.4	7.9	[a]6.0	[a]6.0	5	---	-----	7.0
8.4	12.0	[a]6.0	[a]6.0	6	---	-----	8.4

[a]Circular light source.
[b]Schlieren image dim and difficult to evaluate.
[c]Illumination low at edges of schlieren image.
[d]Illumination low at top and bottom of schlieren image.

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