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A High-speed Camera for the Photography of Shock-wave Oscillations in a Wind Tunnel

By

D. W. HOLDER and R. J. NORTH,
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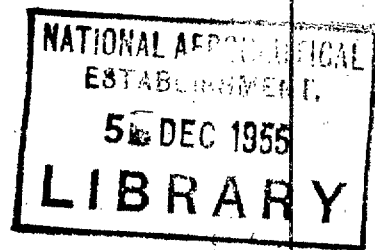
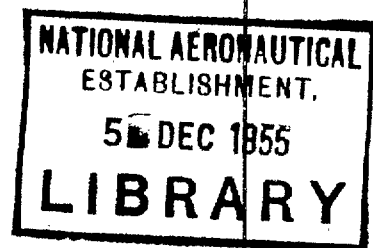
W. G. STANDRING and J. S. T. LOOMS,
of the Electricity Division, N.P.L.

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Summary.—A camera has been developed which enables oscillations of shock-waves and of other quasi-stationary phenomena in a wind tunnel to be photographed by either the schlieren method or the shadowgraph method at speeds up to 2000 frames per second, and with exposures of the order of 1 microsecond.

Photographs of an oscillation which occurs when the critical Mach number is exceeded at low Reynolds number on an EC 1250 aerofoil are included as examples.

1. *Introduction.*—The camera was designed to photograph two main types of oscillation, namely pitching oscillations of an aerofoil as a whole, as in derivative measurements, and oscillations of the shock-waves and the wake on a fixed aerofoil. It was thought that observations of the second type of oscillation might help in the understanding of aileron buzz and of buffeting phenomena at high speeds, including buffeting occurring close to maximum lift.

The derivative measurements at high Mach number planned at the National Physical Laboratory involve oscillations at about 10 c.p.s. in the earlier experiments, rising in later experiments to 100 c.p.s. or more. Thus, assuming that about 20 photographs are needed per cycle, the range of photographic frequency to be covered is roughly 200 to 2000 c.p.s. It was more difficult to decide on the frequencies which would be encountered in shock-wave oscillations on a fixed wing: The frequency parameters found in observations of aileron buzz and of the downwash fluctuations behind a fixed wing suggest that the frequency may be between 1000 and 2000 c.p.s. for the model scale (5-in. chord) used in the 20-in. \times 8-in. Wind Tunnel at the N.P.L. An oscillation whose frequency was of this order has been observed¹ in the 20-in. \times 8-in. wind tunnel by Hilton and Fowler. Because of the increased model scale, the frequency would be expected to be lower in the new tunnels to be built at the N.P.L. When the camera was designed, no data were available on the frequency of oscillations occurring at high speeds close to maximum lift.

It was considered that it would be sufficient to design the camera to work at photographic frequencies up to 2000 frames/sec. This is by no means a high frequency, for speeds up to 400,000 frames/sec have been obtained^{2,3,4} by using a device such as a rotating prism or a moving

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lens to compensate for the motion of the film, and speeds up to 10×10^6 frames/sec⁵ by splitting the photographic image into strips which are later recombined during the printing process. When, however, the object to be photographed moves in a direction either parallel or perpendicular to the velocity of the film the only way of obtaining satisfactory photographs is to employ a short exposure, and provided that the exposure time is small compared with the interval between successive photographs, no compensation is then necessary for the motion of the film. This condition was satisfied in the present case, for it was estimated that an exposure of the order of 1 microsecond or less was necessary to give a sharp photograph. Since it is known that for a given amount of light the duration of a light pulse (often defined as the time during which the intensity of the light is greater than $1/3$ the maximum value) may be reduced by choosing a high voltage, it was decided to use a 9 kV spark at atmospheric pressure as light source. This system had the additional advantages that the size of the source was small (about 1-mm diameter) thus making it directly suitable for shadowgraph photography, and that the photographs were directly comparable with single-exposure photographs that are taken at the N.P.L. by a similar method.

2. *Description of the Camera.*—The general layout of the components of the camera, arranged for shadowgraph photography, is shown in Fig. 1. Direct current from the high-voltage power-pack passes through a contactor, which is used to start and stop the current, and charges a condenser through an inductance. This condenser discharges through a primary spark-gap when a secondary gap is spanned by bridge pieces attached to a rotating drum. The primary gap acts as the light source, and is placed at the focus of a lens or mirror thus producing a parallel beam of light which passes the model in the wind tunnel and finally falls on a 70-mm photographic film held round the outside of a rotating drum. The apparatus is adjusted so that when the contactor is closed a single spark discharge occurs at the primary gap every time the secondary gap is bridged, and a series of separate photographs are therefore recorded on the film. To prevent multiple exposures, a shutter is used to ensure that photographs are taken during a single revolution of the drum only. This shutter is operated by a 110-volt d.c. supply through a relay circuit and a pair of brushes running on a rotating contact fixed to the drum. It is automatically brought into operation a short time after the high-voltage contactor is closed by means of a low-voltage contactor.

In order to operate the camera, the drum is run up to the required speed and the switch controlling the supply of current to the contactor magnet is pressed. This starts the spark discharge, and when this has had time to become steady the shutter is automatically opened and then closed after the drum has turned once, remaining closed during further revolutions. The magnet switch is then released, the drum is stopped and the film removed for development. The time taken for the complete sequence of loading and unloading the film, starting and stopping the drum, and taking the photographs is of the order of four minutes.

Details of the components of the camera are discussed in later sections. The design is such that the camera can be used for a variety of experiments made with different optical systems, and in different wind tunnels.

2.1. *The Rotating Drum.*—The drum may be driven at any speed up to 3000 r.p.m. by a $\frac{1}{2}$ -h.p. d.c. shunt motor, or at 3000 r.p.m. by a synchronous motor. The speed is indicated on a scale situated close to the motor controls by means of an electrical tachometer pick-up attached to the motor shaft.

Details of the drum are shown in Figs. 2 and 3. It consists of a rotor D machined from an aluminium casting, and keyed to the shaft HH which is connected to the motor through a flexible coupling G. The rotor is provided with slots S_1 and S_2 on its inner and outer

surfaces* for supporting the photographic film, and carries twenty evenly spaced copper bridge pieces C mounted on a Tufnol ring which acts as an electrical insulator.

The rotor rotates close to a stator T which is constructed mainly of Tufnol and carries two pairs of copper contacts AA and BB which are arranged to clear the bridge pieces C by about 0.01 in. When twenty light flashes are required per revolution the primary gap is connected in series with the gap BB so that a discharge occurs every time one of the bridge pieces C passes between them. For forty flashes per revolution the pairs of gaps AA and BB are connected in parallel and placed in series with the primary gap. Compressed air is supplied through one of the nozzles N in order to help extinguish the arc formed between the gaps and bridge pieces; the air leaves through the vents V. Each contact and each bridge piece is 3-mm thick and the opposing edges are 25-mm wide. After about 2000 operations of 1 second duration there is no sign of appreciable wear or overheating of the contacts.

2.2. The Shutter.—The shutter was designed to fulfil the requirements of equal and short operating times in both directions by using two coils wound on a light former moving in the annular gap of a loud-speaker permanent magnet. It was necessary to use coils wound over $\frac{1}{2}$ -in. to obtain the shutter-blade movement required, and it was more convenient in this instance to use two windings in opposite senses than to reverse the current in a single coil. The moving-coil system was adopted in order to obtain small mechanical and electrical time constants.

The shutter blade should move across the beam of light from the source as swiftly as possible to avoid the loss of frames by partial exposure and it is obviously an advantage to have the shutter as close to the source as possible. The present design has a longer stroke of shutter blade than is necessary, since when it was made it was not clear what type of source would be used finally. It will be possible to improve the characteristics of the shutter by shortening the stroke and decreasing the mass of the moving coil. The total operating time of the relay system and shutter, measured on the film, appears to be $4\frac{1}{2}$ milliseconds, of which $2\frac{1}{2}$ milliseconds is due to the successive closing of two of the relays necessary to energise the coils.

The construction of the shutter is shown in Fig. 4. The permanent magnet is of the ordinary loud-speaker type the only modification being a slight increase in the annular gap to provide greater clearance for the moving coils.

2.3. The Relay System.—The function of the relay system is to arrange that the shutter does not operate until required, that it then opens for one revolution only, and thereafter remains closed. This is accomplished by the circuit† shown in Fig. 5. When the contact on the drum is first made after the 110-volt d.c. switch has been closed, relay H1 closes and H2 and H3 follow. As H3 closes coil A is energised and opens the shutter. When the drum contact breaks again H1 opens allowing H4 and H5 to close. During the ensuing revolution of the drum H1 is open, and H2, H3, H4 and H5 are closed. When the contact is next made on the drum, H1 closes again allowing H6 and H7 to close: H6 interrupts the supply to coil A and energises coil B, closing the shutter. The shutter remains closed during succeeding revolutions of the drum since all relays except H1 are held in, and subsequent operation of H1 has no effect. In order to expose the full length of film on the drum it is necessary that the shutter should open and close with the same delay, and that the variations in the delay should be small. Accordingly, the circuit is arranged so that the operating times in each direction should be the same and as short as possible.

* The slot on the inner surface was provided in case difficulty was found in keeping the film on the outside. Preliminary tests showed that the ultimate stress of celluloid was about 5000 lb/sq in., and that a single strip of cellulose adhesive tape (Durex Abrasives Ltd.) $\frac{1}{2}$ -in. wide and 70 mm long with one half of the width attached to the film and the other half attached to the surface of the aluminium broke when the tangential load exceeded about 40 lb. These figures provided an adequate factor of safety when the film was on the outside of the drum rotating at 3000 r.p.m., and no difficulties have been encountered in using this arrangement.

† Suggested by Mr. A. Felton of the Electricity Division, N.P.L.

2.4. *The Contactors.*—The contactors are shown in Fig. 6. When direct current is supplied to the electromagnet M, the lever BB is pulled in and the insulating strip AA (attached to BB by springs) moves over, closing the high-voltage contacts XX and YY and thus allowing the spark condenser to charge and the primary gap to start working. The metal wheel W is pivoted at P and is arranged to have its centre of gravity at G. When the pin Q is released by the displacement of AA, this wheel starts to rotate until finally the low-voltage contacts U and V controlling the supply to the shutter close about $\frac{1}{2}$ second after the closure of the high-voltage contacts. The felt damping pad D was found to be necessary to prevent U and V from bouncing. On cutting off the supply to the electromagnet M, BB and AA fall back onto a stop under the action of the return spring S and the high-voltage and the low-voltage gaps are opened.

2.5. *The High-Voltage Supply.*—The spark is obtained by the discharge of a condenser (Fig. 1) placed across the primary gap. The capacity of this condenser is 0.1 microfarad for frequencies up to 1000 sparks/sec, and is halved for frequencies between 1000 and 2000 sparks/sec. This reduces the amount of light produced by each discharge, but since for schlieren photography the diameter of each photograph has also to be halved in order to obtain 40 exposures for each revolution of the drum the exposure remains adequate. The spark condenser is charged from a $4\frac{1}{2}$ -kV d.c. source obtained from a 3-phase a.c. 50-c.p.s. supply by means of three mercury vapour rectifiers. This power pack (Fig. 7) contains a reservoir condenser of 20 microfarads. The spark condenser is connected to the $4\frac{1}{2}$ -kV source through an inductance of 13.5 henries by means of the high-voltage contactor (*see* 2.4 and Fig. 6). After a few discharge cycles the spark condenser reaches a voltage of 9-kV at each cycle, and the shutter is then worked by the auxiliary low-voltage contactor (*see* 2.4 and Fig. 6).

2.6. *The Light Source.*—Preliminary experiments were made to investigate the influence of the material of the electrodes of the primary spark-gap on the light output. It was found that the light output increased, and the rate of decay fell, as the volatility of the metal was raised. The light output in a direction at right-angles to the spark axis from one discharge across a 1-mm gap measured by an integrating photoelectric flashmeter having the same spectral response as the eye was about 0.1 candle second for copper electrodes, and about 0.2 candle second for cadmium or magnesium electrodes. The spark-gap used in the work described in the present paper was between the ends of two $\frac{1}{8}$ -in diameter magnesium rods about 1-mm. apart.

2.7. *The Characteristics of the Spark.*—When the loop of the discharge circuit is made as small as possible the circuit inductance is about 0.4 microhenry. The discharge current is a damped oscillation of period about 1.3 microseconds and of maximum amplitude about 4000 amperes. An oscillogram of the current is reproduced in Fig. 8. If it is required to have the spark and the camera at some distance apart, an 8-metre length of concentric cable having an inductance of about 0.3 microhenry can be included in the circuit. The current $V\sqrt{C/L}$ is reduced and the period $2\pi\sqrt{LC}$ increased; the total light emitted is decreased by about 30 per cent. An oscillogram of the light output with cadmium electrodes, obtained by the use of a photomultiplier (type 931 A) and amplifier, is reproduced in Fig. 9. It will be seen that the greater part of the light is emitted in the first half-cycle of the oscillatory discharge. The light intensity cannot be marked in a scale of lumens because the photomultiplier has a very different spectral response to that of the eye.

3. *Optical Apparatus.*—For the shadowgraph system shown in Fig. 10 the lack of sharpness of the image due to the finite size δ of the source is given by $h\delta/f$. Now the sensitivity⁶ of the arrangement is roughly proportional to h and, the size of the source being fixed, the best way of obtaining sharp photographs is to use a lens or mirror of long focal length f to produce the parallel beam of light which is used to illuminate the object. Unfortunately, however, the illumination in the parallel beam of light is given by BA/f^2 where B is the brightness and A is the area of the source, so that if the focal length is too large the photographic exposure may become inadequate.

In a preliminary experiment in which shadowgraph photographs were taken of a rotating disc, a focal length of 4 ft was used and gave satisfactory sharpness. A focal length of 3 ft was used in the preliminary wind-tunnel photography but was found to give poor definition, and the focal length was increased to 9 ft for the remainder of the work. With this focal length it was found that both the sharpness and the exposure were satisfactory (*see* Figs. 12 and 13). A pair of mirrors of 9-ft focal length were used for the schlieren photography, the arrangement being that shown in Fig. 11.

4. *Observations of the Flow Round an Aerofoil.*—The camera was used to photograph an oscillatory flow which occurs⁷ on a 2-in. chord aerofoil of EC 1250 section at low Reynolds number ($R \approx 0.7 \times 10^6$), and at Mach numbers slightly above the critical. The frequency of the note emitted from the aerofoil suggested that the frequency of the oscillation was about 900 c.p.s. rising suddenly at a higher Mach number to about 1800 c.p.s. The maximum photographic frequency of the camera was, therefore, not sufficient* to enable the flow changes within a single cycle to be recorded directly, but, the oscillations being periodic, the changes within a cycle could be observed by photographing different stages of successive cycles.

Examples of the photographs obtained by the shadowgraph method are reproduced in Figs. 12 and 13, and by the schlieren method in Figs. 14 and 15. The photographs were taken for two Mach numbers, 0.813 and 0.822. The frequency of the note emitted for $M = 0.813$ was 900 c.p.s. and for $M = 0.822$ it was of the order of 1800 c.p.s. The photographic frequency was of the order of 1000 frames/sec.

The photographs confirm that the motion is periodic and that the frequency of the oscillation is proportional to the frequency of the note emitted. At both Mach numbers waves moving upstream† past the aerofoil are visible (*see*, for example, Fig. 14m, 14n, 14o and Fig. 15m, 15n, 15o). These probably pass round the outside of the region of locally supersonic flow close to the surface, and then into this region from the sonic line producing the inclined disturbances shown in some of the photographs (*see*, for example, Fig. 12f) which are then reflected from the surface of the aerofoil.

5. *Acknowledgements.*—Mr. H. Deacon of the Aerodynamics Division was responsible for the detailed design of the rotating drum. Mr. W. Rich made the drum in the workshop of the Aerodynamics Division.

* This is mainly due to the fact that the chord which was used (2 in.) was smaller than that for which the camera was designed to operate (5 in.). If there is no scale effect the frequencies for a 5-in. chord would be about 0.4 times those for a 2-in. chord.

† The relationship between the frequencies of photography and oscillation is such that they appear in some cases to be moving downstream.

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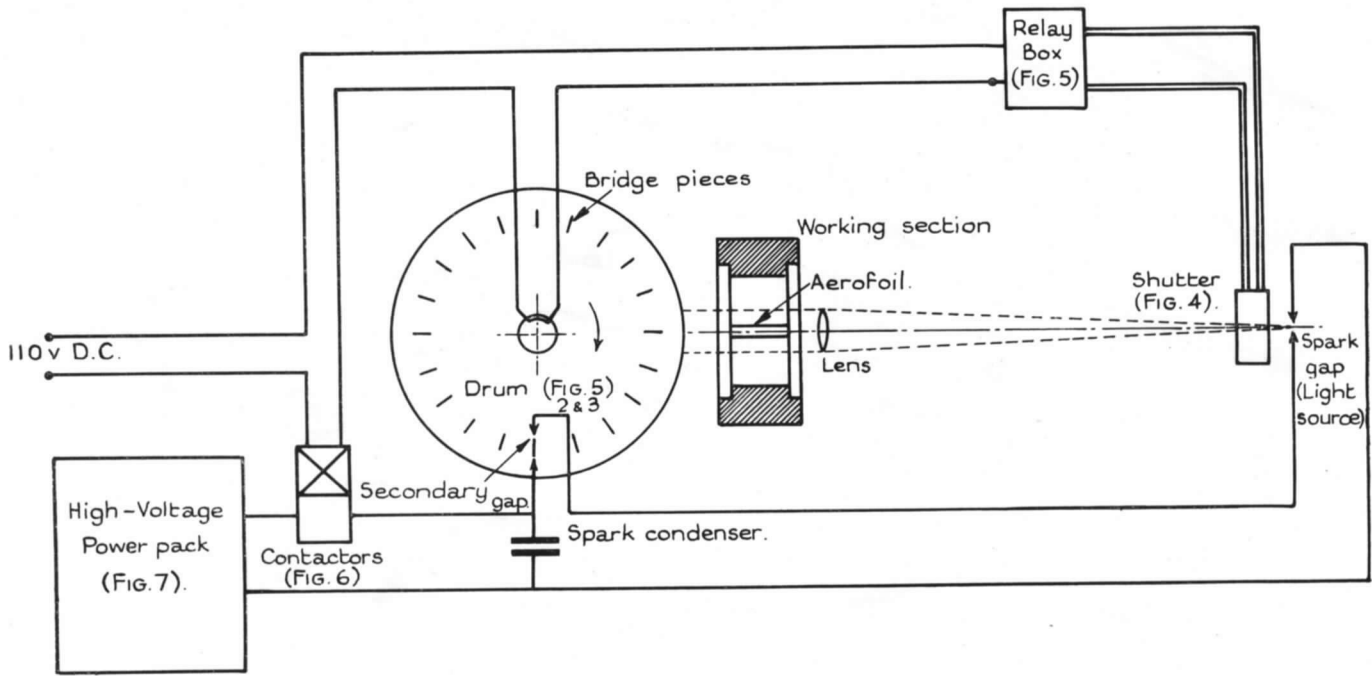
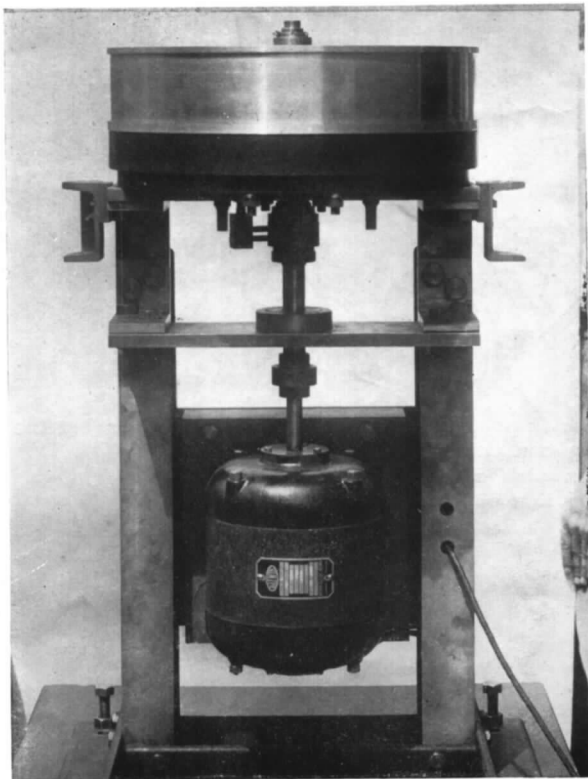
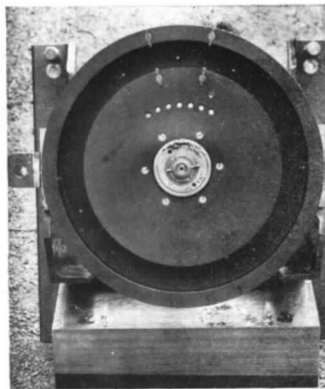


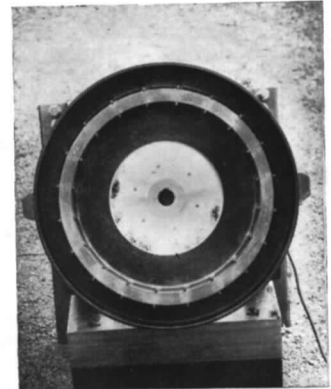
FIG. 1. General arrangement of components.



2a. General arrangement.

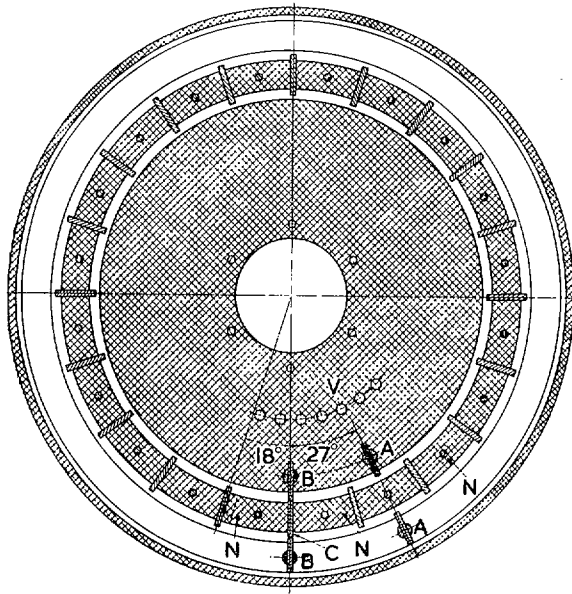


2b. The stator.

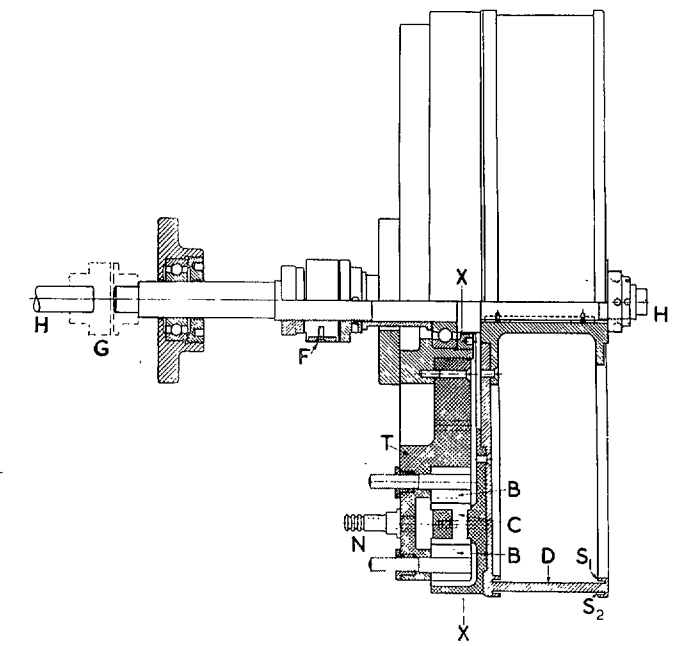


2c. The rotor.

FIG. 2. Photographs of the rotating drum.



Section on line XX



Tufnol

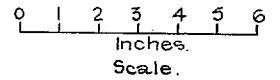
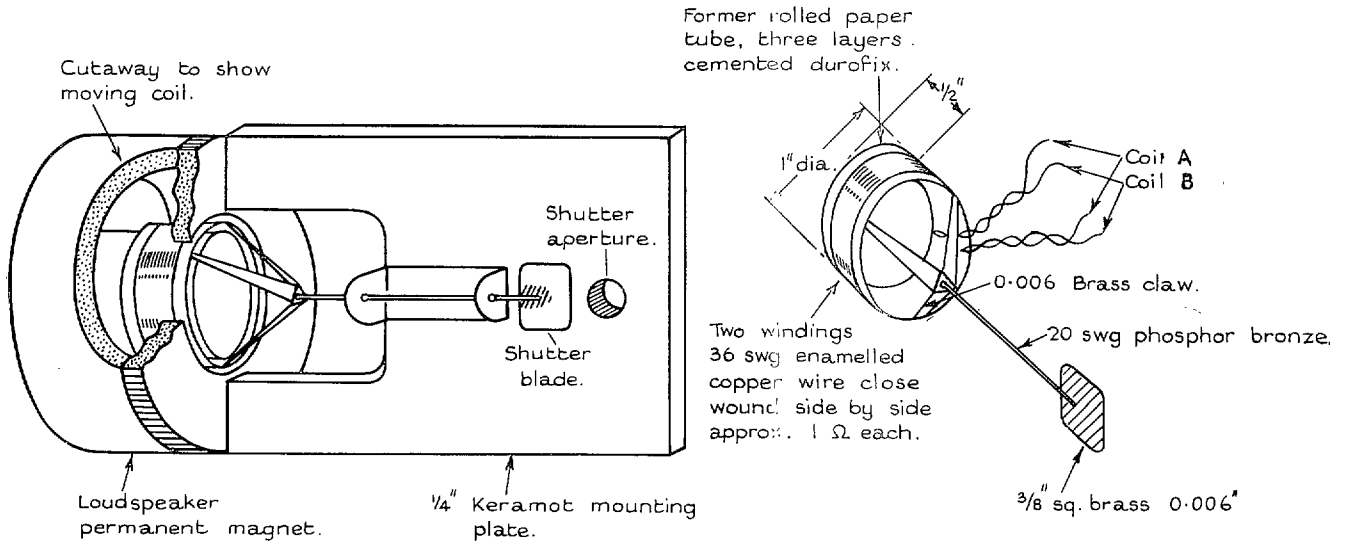


FIG. 3. Details of camera drum.



Fixings and shutter leads omitted for clarity.

General View.

Detail of moving coil.

FIG. 4. Shutter.

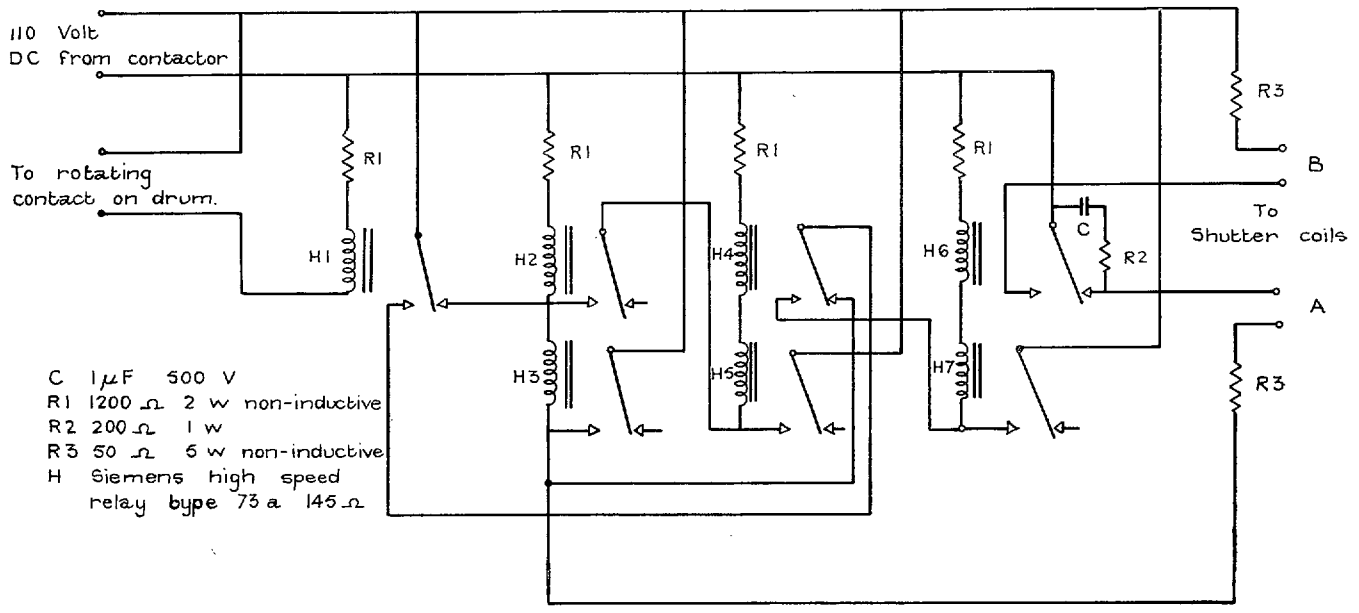


FIG. 5. Relay circuit to open shutter for one revolution.

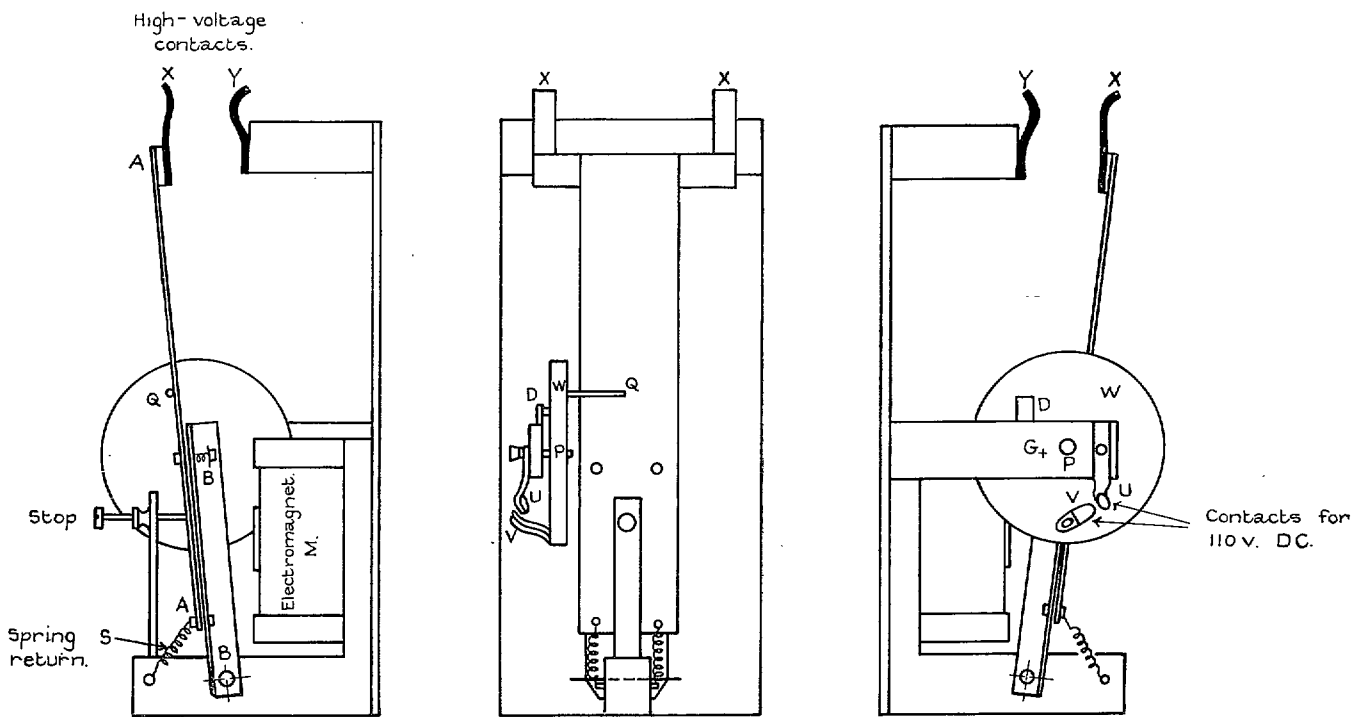


FIG. 6. Arrangement of contactors.

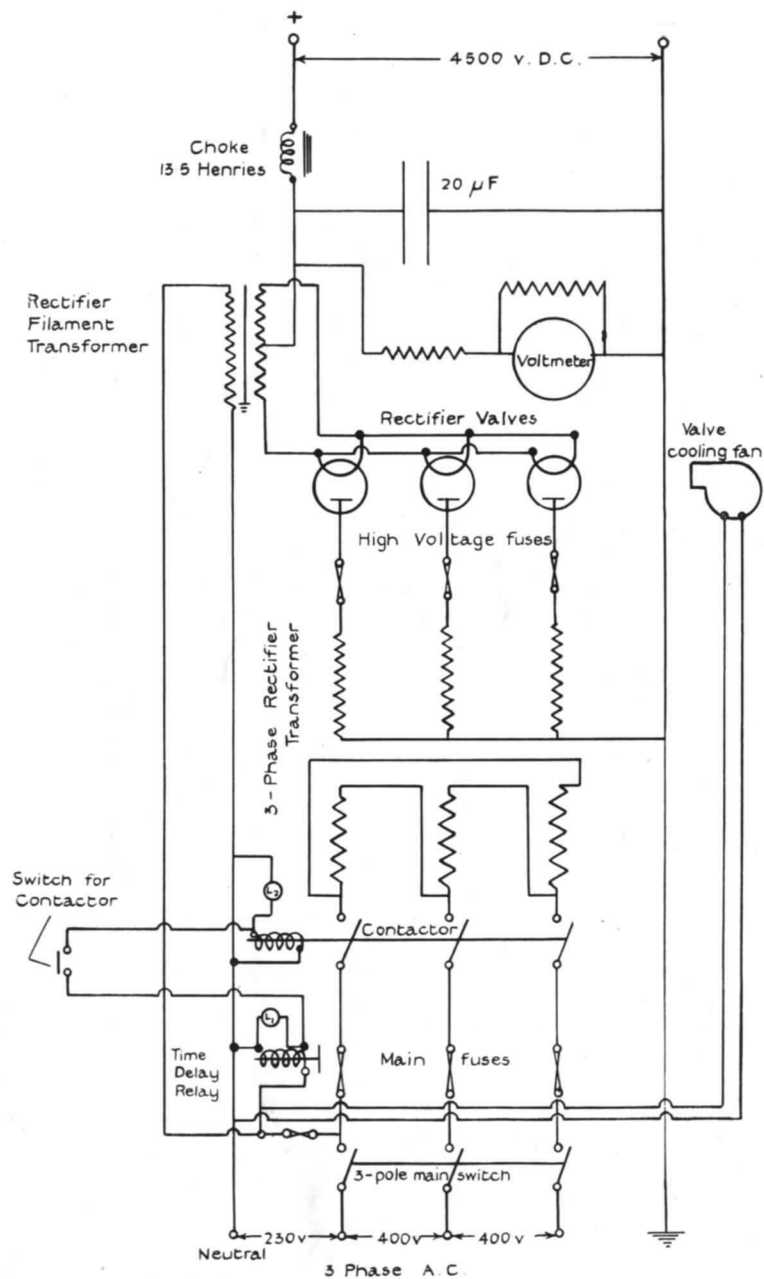


FIG. 7. Circuit of high-voltage power pack.

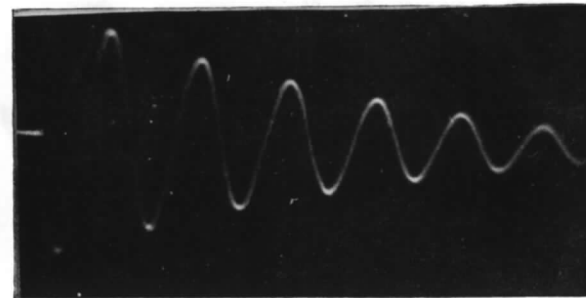


FIG. 8. 4 kA discharge current.
Time scale as in Fig. 9.

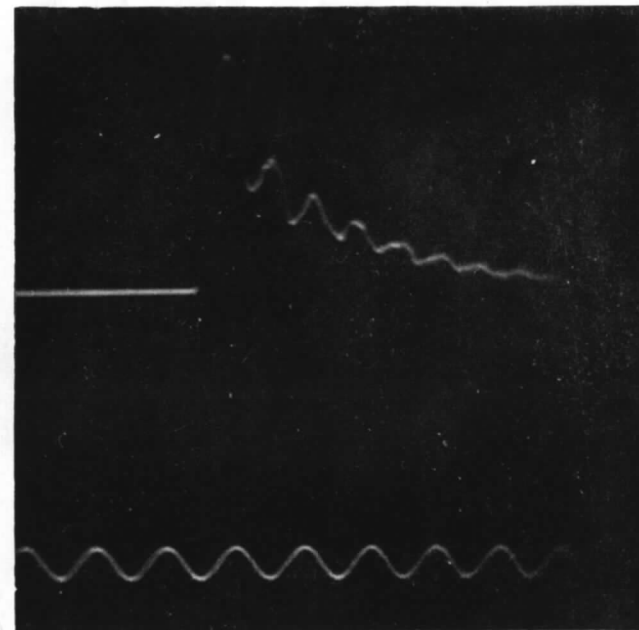


FIG. 9. Variation of light output with time.
Timing oscillation 1 mc/sec.

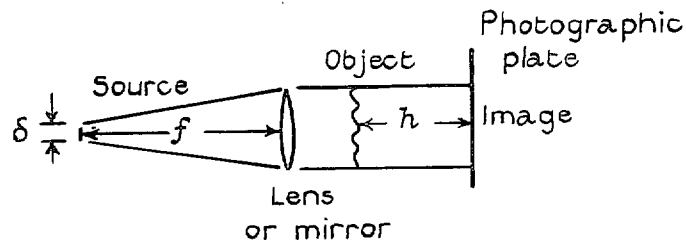


FIG. 10. Shadowgraph apparatus.

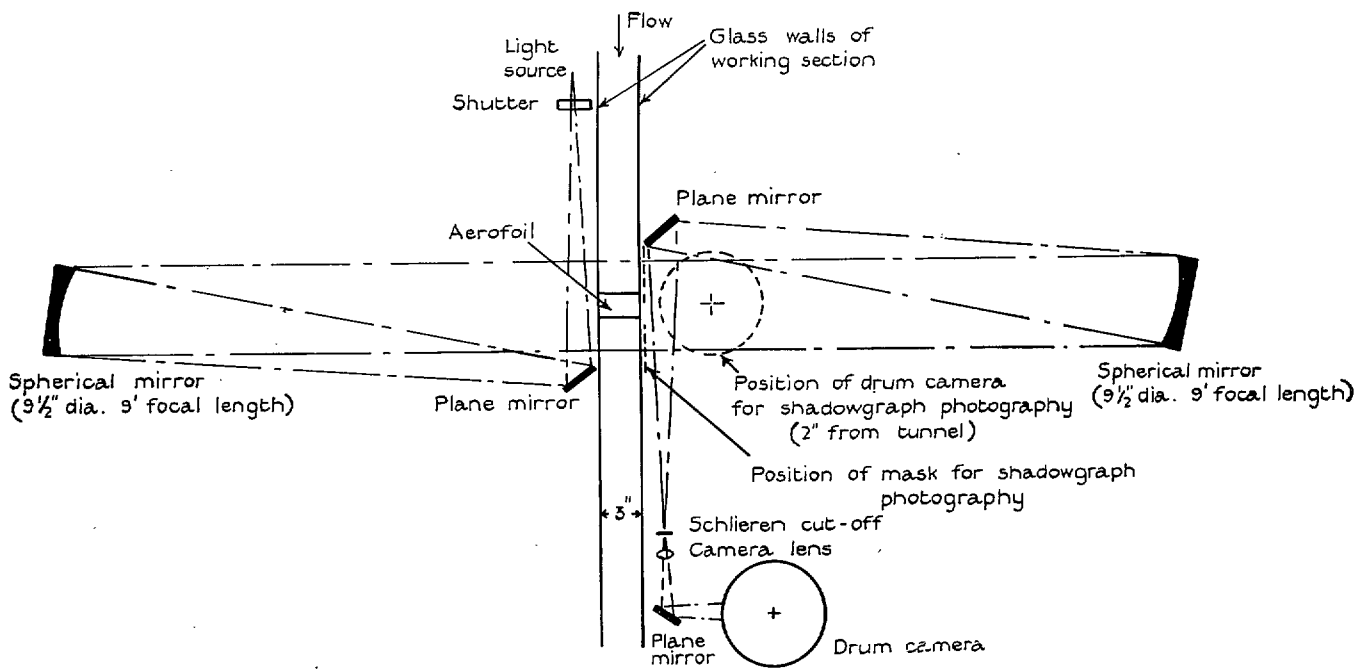


FIG. 11. Optical systems for schlieren and shadowgraph photography.

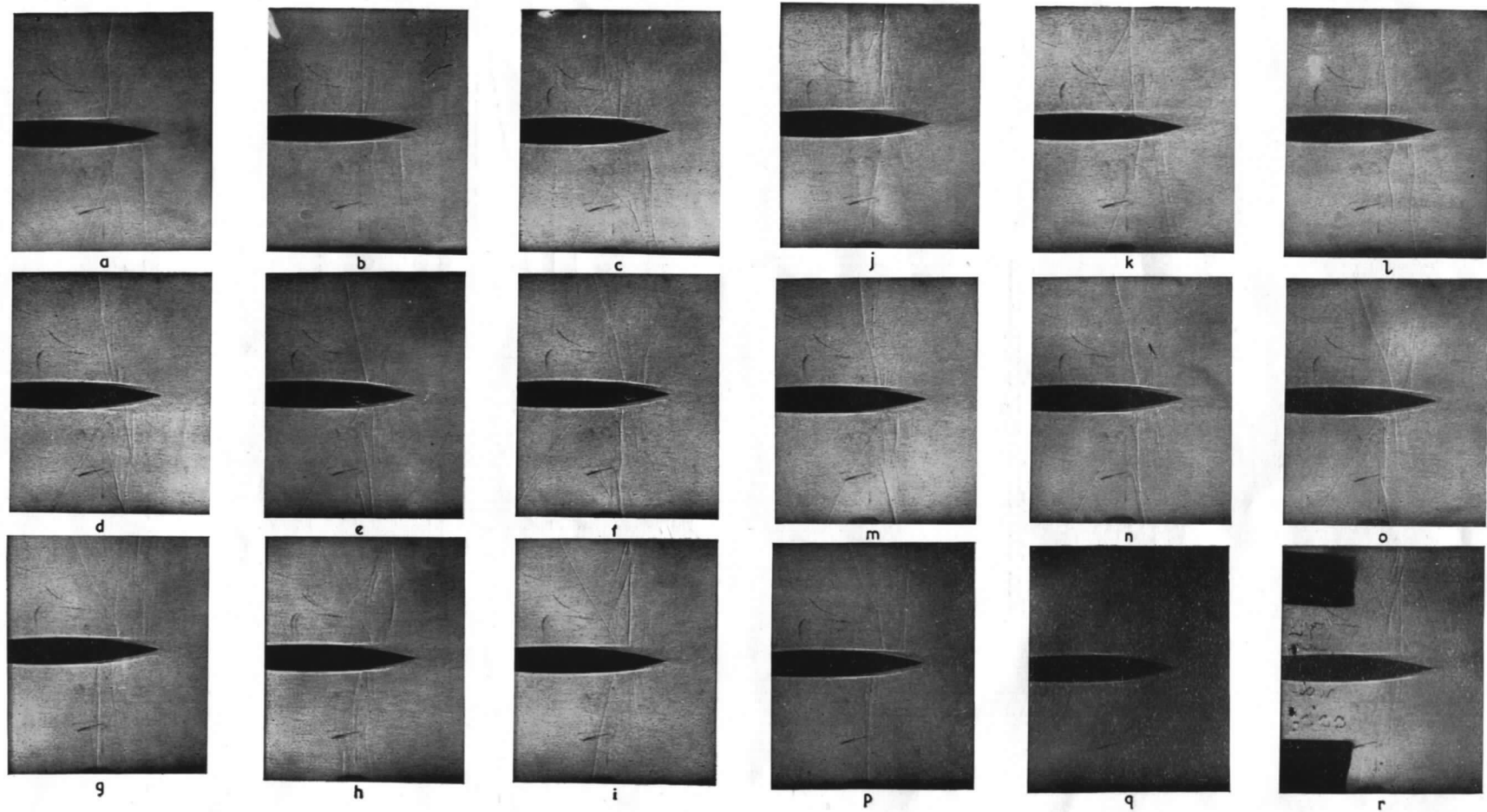


FIG. 12. Shadowgraph photographs at $M = 0.813$. EC 1250 aerofoil.

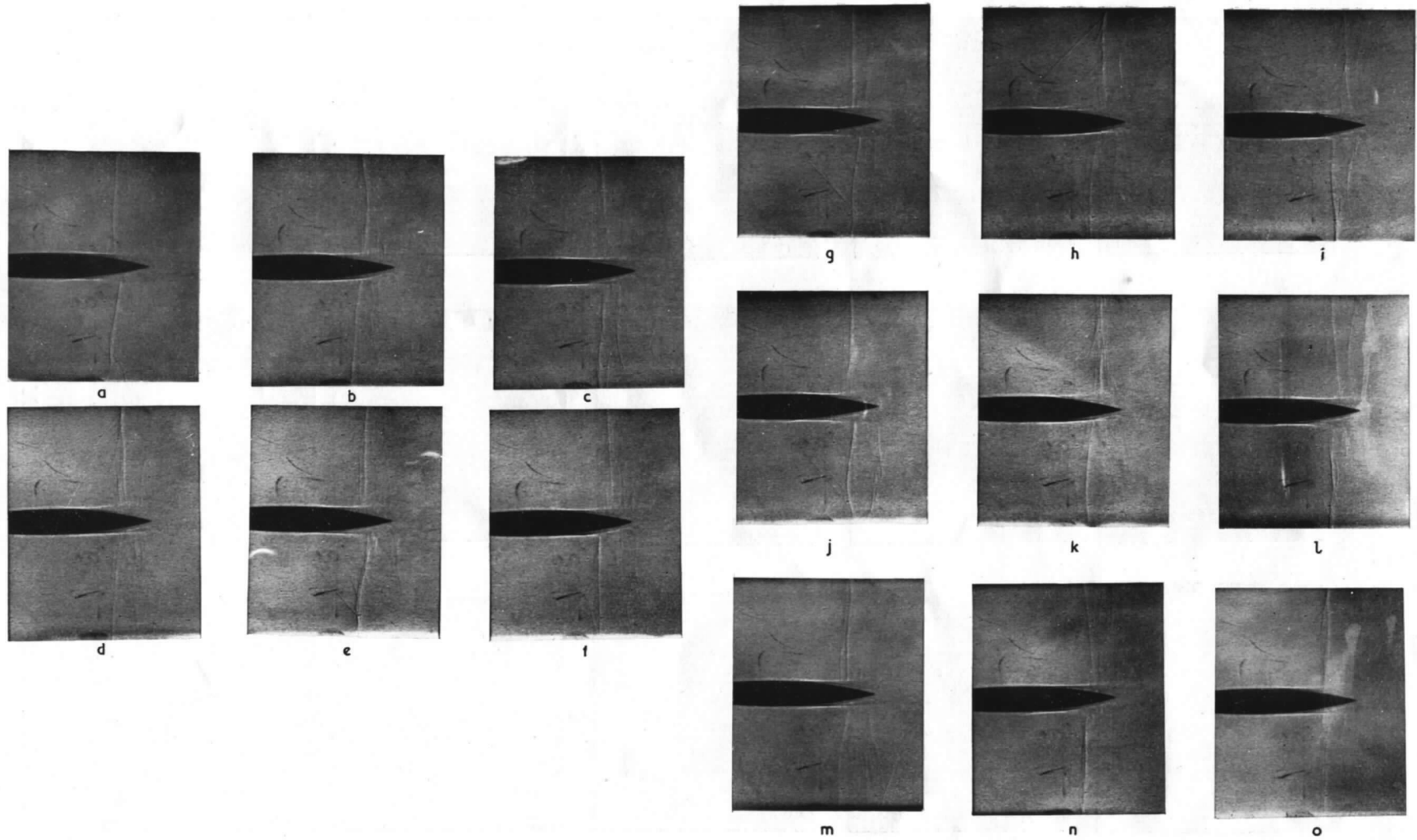


FIG. 13. Shadowgraph photographs at $M = 0.822$. EC 1250 aerofoil.

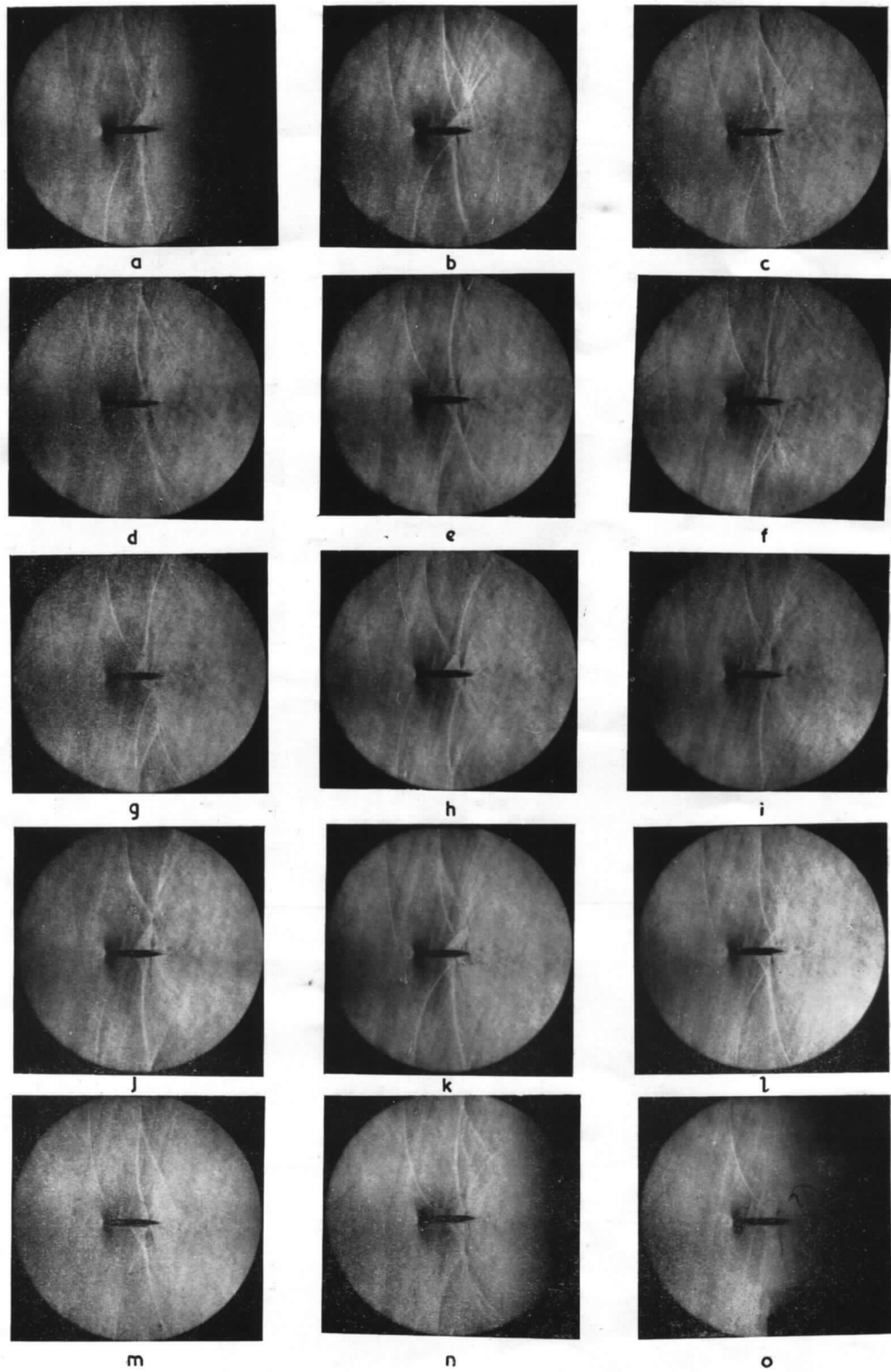


FIG. 14. Schlieren photographs at $M = 0.813$. EC 1250 aerofoil.

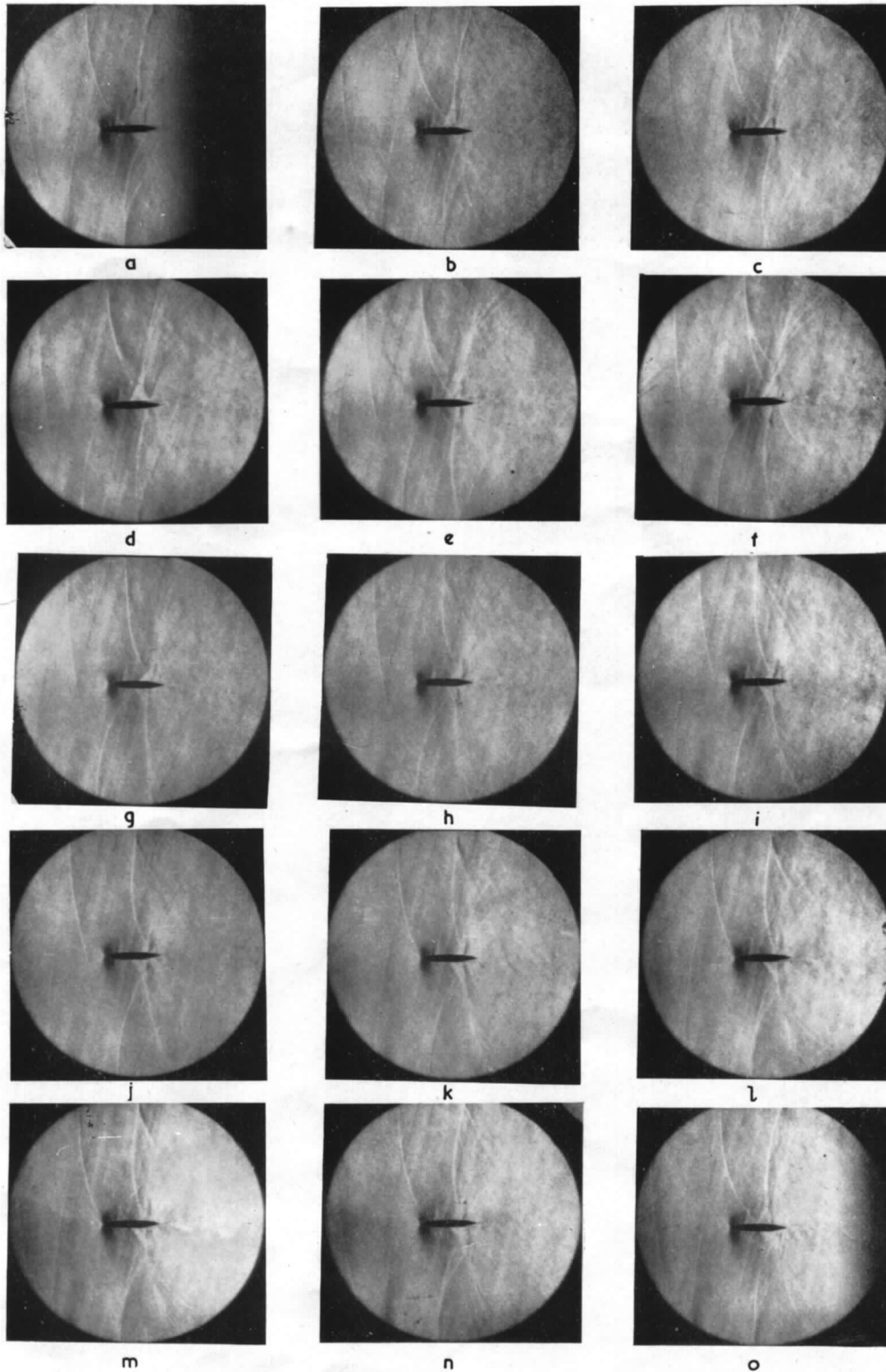


FIG. 15. Schlieren photographs at $M = 0.822$. EC 1250 aerofoil.

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