TRACING CAMERA DSL—I

HARSH VARDHAN*

Defence Science Laboratory, Delhi

Design and performance characteristics of indigenously developed high speed camera whose applications include the study of explosive phenomena and fragmentation are described. Mechanical and optical details of the camera are given and illustrated.

The high speed photographic cameras can be grouped in different classes either depending on the physics of the process involved like optical compensation, image switching, multiplexing, dissection etc. or according to the mechanics of the operation of the camera as for example, continuous film movement, stationary film with rotating mirror, rotating prism, rotating pyramid, rotating aperture and stationary pyramid and lenticular plates etc. A classification following Naslin,[1,2] is shown in figure 1.

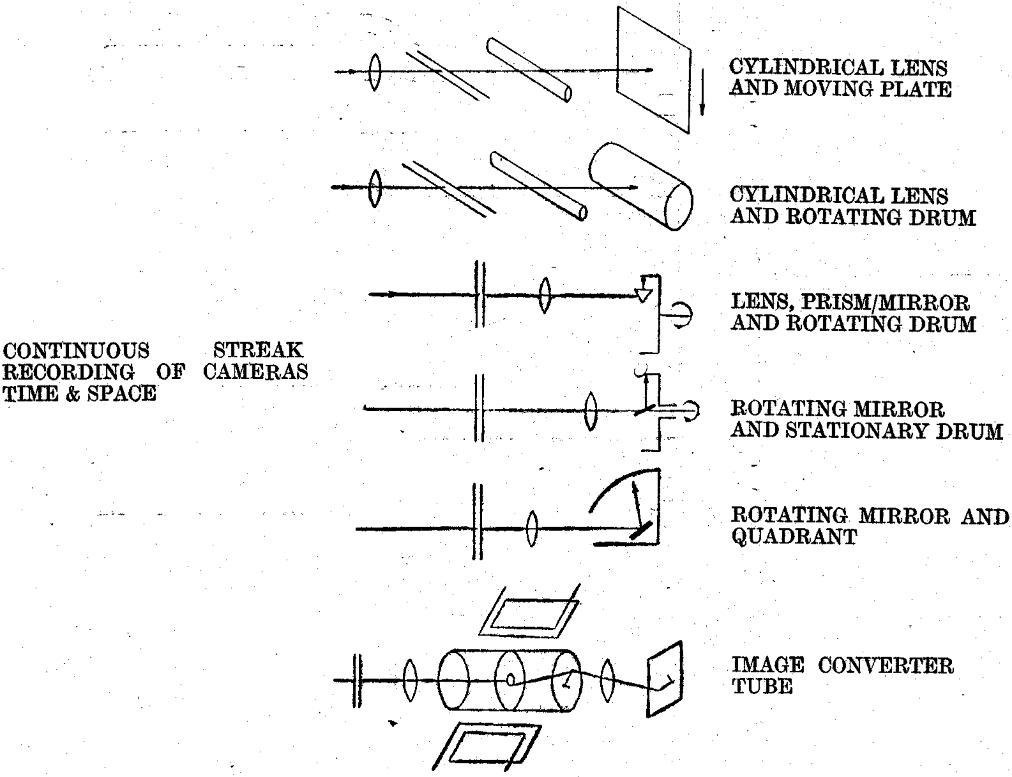


Fig. 1

---

* Now at Solid State Physics Laboratory, Delhi-6

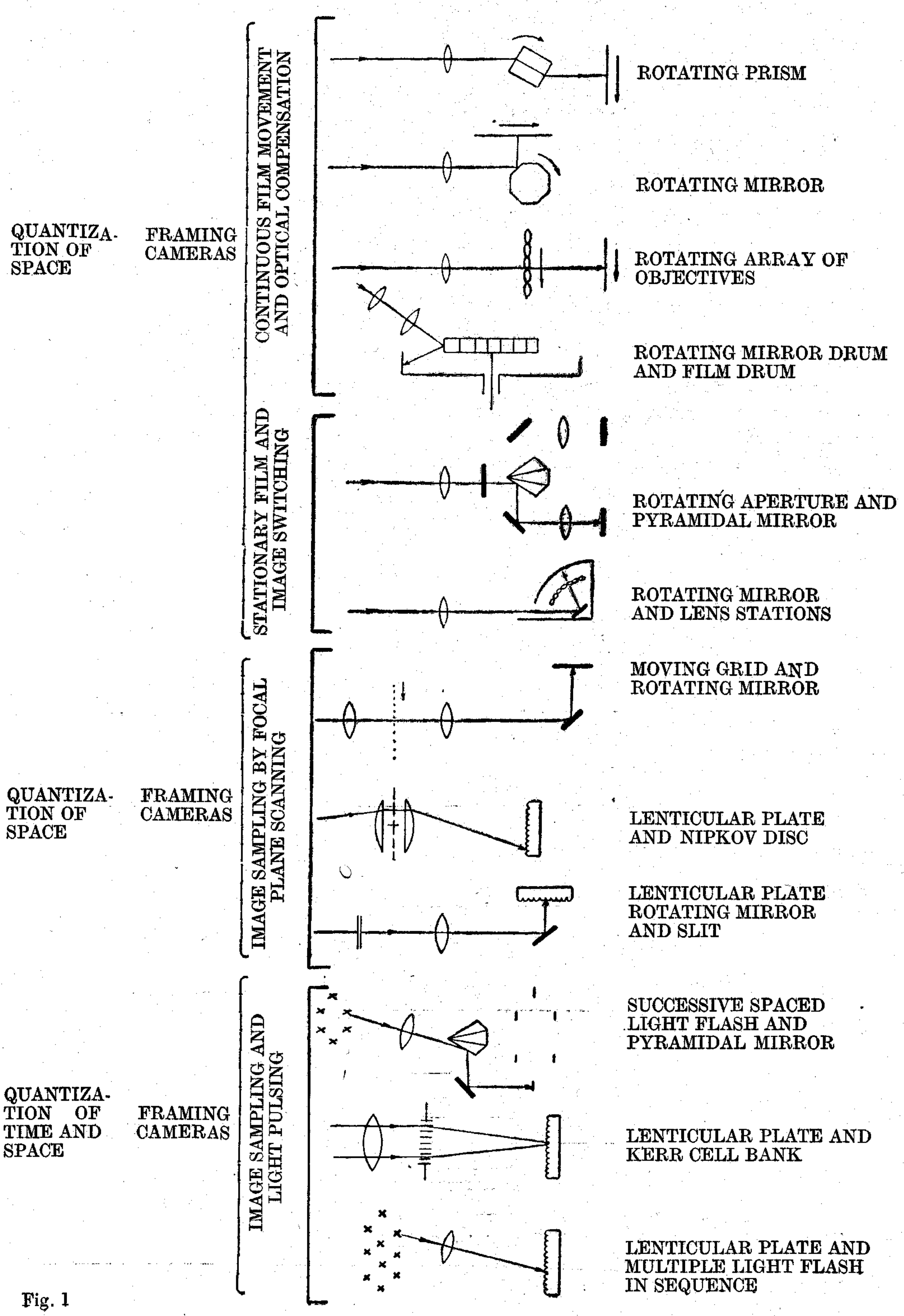

QUANTIZATION OF SPACE
FRAMING CAMERAS
CONTINUOUS FILM MOVEMENT AND OPTICAL COMPENSATION
ROTATING PRISM
ROTATING MIRROR
ROTATING ARRAY OF OBJECTIVES
ROTATING MIRROR DRUM AND FILM DRUM
STATIONARY FILM AND IMAGE SWITCHING
ROTATING APERTURE AND PYRAMIDAL MIRROR
ROTATING MIRROR AND LENS STATIONS
QUANTIZATION OF SPACE
FRAMING CAMERAS
IMAGE SAMPLING BY FOCAL PLANE SCANNING
MOVING GRID AND ROTATING MIRROR
LENTICULAR PLATE AND NIPKOV DISC
LENTICULAR PLATE ROTATING MIRROR AND SLIT
QUANTIZATION OF TIME AND SPACE
FRAMING CAMERAS
IMAGE SAMPLING AND LIGHT PULSING
SUCCESSIVE SPACED LIGHT FLASH AND PYRAMIDAL MIRROR
LENTICULAR PLATE AND KERR CELL BANK
LENTICULAR PLATE AND MULTIPLE LIGHT FLASH IN SEQUENCE

Fig. 1

It can be seen that one type of high speed cameras utilize a rotating mirror and a stationary film. The speed of such a camera would primarily depend on how fast the mirror could be rotated. These basic features suggested that the initial efforts in designing and making of high speed cameras be directed towards cameras involving this scheme. Designs based on this could be fabricated comparatively more easily vis-a-vis the available technical facility.

Three cameras have been made; one tracing camera and two framing cameras. This paper is a report on the tracing camera. The constructional details and performance characteristics are discussed. Except for the bearings and the transistors, the camera is entirely made of indigenous material. One of the main considerations in designing the camera has been that the design should be amenable to the available fabrication processes.

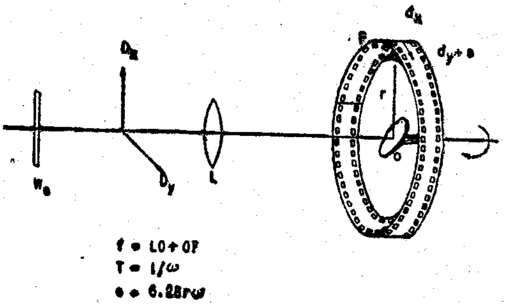


Fig. 2—Optical System

OPTICAL SYSTEM

In the first design of the camera, the face of the mirror *RM* was at 45° to the axis of its rotation. The film *F* covered the entire cylindrical focal plane around the mirror as shown in fig. 2. The position of the objective lens *L* was adjusted such that the object was in focus at *F*. This system had the advantage that no synchronisation with the event was required. As long as the duration of the event was less than the time per revolution of the rotating mirror there would be no danger of re-writing and overlapping of the trace. If the total time of the event was known, the camera speed could be controlled; if not known, a preliminary trial could be carried.

A trace of an exploding wire taken with this camera is shown in Fig. 3. This photograph shows that the camera had a big disadvantage. The 45° rotating mirror

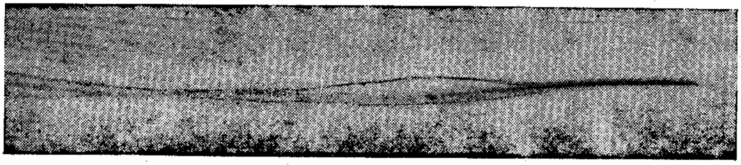


Fig. 3—Trace of the exploding wire

during its 360° excursion gave a 'cyclic twist' to the trace. There are two positions at which the trace band turned over and the traces from different fragments merged in one. After the turn-over, it is generally difficult to distinguish and assign the separate traces to their original counterparts before the turn-over. Since each trace in the band is caused by an exploding fragment, the history of the event is lost. Therefore the optical system has been modified. This latter is treated below in more detail.

The incoming light from the event after passing through the objective L is reflected by a front surface aluminised mirror M on to the rotating mirror RM. The rotating mirror reflects it again and sweeps it across the semi-circular arc of the film at the focal surface of the objective as shown in Fig. 4. In this case the plane of the mirror RM makes a much smaller angle θ with the axis of rotation such that $\tan 2\theta = \frac{ab}{bc}$ provided that the light beam cbA rotates in a plane normal to the axis of rotation. The distance ab can be made small by positioning the mirror M as close to b as possible without interfering with cbA and by making cb large, that is, by increasing the diameter of the film semi-circle. This in turn would need a longer focal length objective combination.

When the mirror RM rotates through an angle ϕ the reflected beam cbA sweeps through angle 2ϕ. Thus, for registering a photograph at the two ends of the horizontal diameter the mirror has to be only at 45° either side of the vertical. If the mirror rotation rate is ω rps., the beam rotates at 2ω rps. Then if r is the radius of the film semi-circle in millimeters, the writing speed S is given by $12 \cdot 56\, r\omega$ mm per sec. It is directly dependent on the mirror rotation speed and the film circle diameter. Further, since the film covers only a half circle, the total event recording time $T = \frac{\pi r}{4 \pi r \omega} = \frac{1}{4\omega}$.

Exposure time τ was defined by Edles and Whittaker[3] as the time of passage of the image over a point at the focal surface. This is valid in the present case also, and following their treatment—

$$\tau = \frac{mW_s}{4r}$$

where m is the magnification of the objective and W_s is the width of the slit. The resolving power P is the reciprocal of τ.

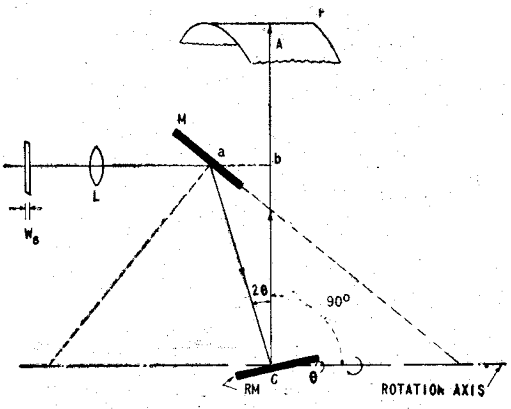


Fig. 4—Rotating Mirror

The inclination of the mirror *RM* to the axis of rotation could cause some defocussing and hence loss of definition by introducing a path difference between rays reflected from different points at its surface. Looking at the vertical cross-section through the axis of rotation two peripheral rays of the light beam are directed as in Fig. 5. The $\angle \rho = \frac{1}{2} \angle bac$. When the ray 1 strikes the mirror *RM* at *P′* the ray 2 would have been at *P* for no path difference. However, somewhere between *M* and *P* it gets reflected. If the reflected beam is perpendicular to the axis of rotation, which also is the axis of the cylindrical focal surface, no path difference will be introduced if the ray 2 is reflected at *N* such that $MN+NR=MP$. The inclination of the line *NP′* with the rotation axis thus defines the angle θ which *RM* should have for not introducing any path difference. Point *N* can be located by solving—

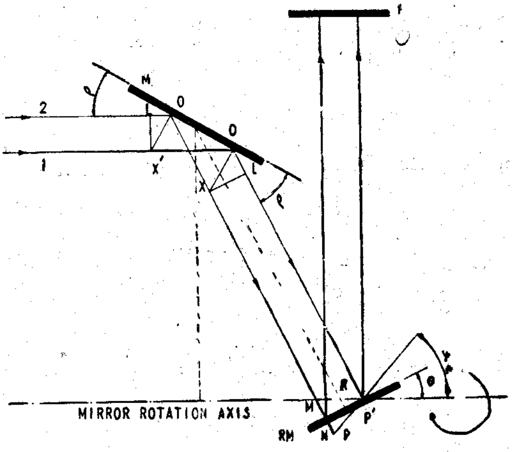
$$\frac{NR}{MN} = \cos\Psi \qquad \text{where} \quad \Psi = 90 - 2\rho$$

$$NR+MN = \mathrm{PP}' \tan\Psi \quad = LX' \tan\Psi = d \tan\Psi$$

$$\frac{NP}{d} = \frac{NR}{d} \sin(\Psi - \theta).$$

where $LX' = d$ is the effective diameter of the incident beam. In a typical case where $\rho = 30°$, <o comes out to be 12° for $d=25$ mm.

Now looking at the system along the axis of rotation of the mirror from the front of the camera towards the mirror, two limiting cases arise : (*i*) when the mirror is parallel and (*ii*) when the mirror is at 45°. It is evident from figure 6 *a* and *b* that no path difference is introduced in either case. Theoretically this arrangement of mirrors permits a very



F g. 5—Periferal rays of the light beam

high quality image definition. It must, however, be remarked that in the foregoing discussion parallel rays have been considered. In practice the rays are convergent. Other factors like curvature of the focal surface and departure from perfectness of the other optical surfaces etc. will contribute to the loss of definition. A small rotation of the image is still there and depends on the angle *acb* in Fig. 4.

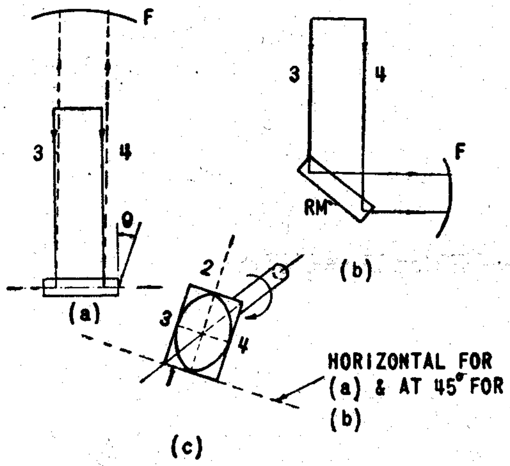


Fig. 6—Limiting cases

Another factor is the influence of the centrifugal forces on the mirror when rotating at high speed. For a mirror of the type used in this camera the distortion would be somewhat as shown in figure 7 *a*, *b* and *c*. At the speed at which this camera operates no perceptible distortion has been noticed so far. A mathematical evaluation of the influence of centrifugal forces is yet to be done.

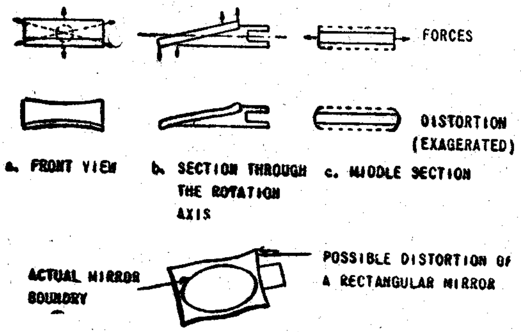


Fig. 7—Distortion due to centrifugal forces

THE TURBINE

Very little is reported about compressed air turbines such as are used in the high speed cameras. Beams[4] *et al*, have done a lot of work on high speed rotors. Most of their work is on rotors with a vertical axis of rotation and the rotor floating in air or gas.

One such rotor as described by Beams[5] and Ford[6] was made and successfully driven. However, it was found inconvenient for adapting to drive the mirror for this camera. Buck[7] has described a turbine with liquid bearings. In his paper while paying tribute to Beams' high skill and experience in high speed rotors, he writes in reference to a horizontal axis turbine—"Lacking the skill and know-how of Professor Beams' long experience we were unable to get the turbine off the test stand without burning its bearings". Obviously, therefore, in absence of initial experience of making such equipment an attempt for making such sophisticated ultra high speed rotors would not have been wise. It was decided to start with ball bearing mounted turbines. The various types of turbines designed, made and studied are reported elsewhere.

In this camera the mirror is spun by means of a compressed air turbine designed like a Pelton wheel. The rotor has machined vanes at its periphery. The vanes are cut askew with the axis of rotation. It is force-mounted on a mild steel spindle and balanced. The spindle rotates in ball bearings of 0·25 inch bore diameter. The turbine body consists of two parts, one rectangular and other conical circular attached to each other through accurately machined seats. The rectangular section carries the compressed air jet assembly and the demountable air filter. The jet holes are 0·4 mm in diameter placed 5·0 mm away from the vane at its maximum-hit position. The position of the jets around the circumference is so arranged that when one jet is being cut off by the vane following the one which is moving under the impact of the jet, the other jet is striking almost full on a vane diagonally opposite. The conical part carries at its apex, one of the ball bearings in a precisely machined seat. The slots are the exit ports for the spent up outgoing air. The other bearing is mounted on the camera boy. The ball bearings used were locally available foreign made. Two seats have since been changed. Due to several factors it is not possible to give an estimate of the total working life of the bearings under actual working conditions.

The pressure speed characteristics of such a turbine are shown in Fig. 8.

A drum to damp any oscillations in the incoming compressed air is located directly under the turbine. This also acts as a trap for any condensed moisture in the line. A hand operated fine-control air valve at the entry end of this drum allows for precise speed control.

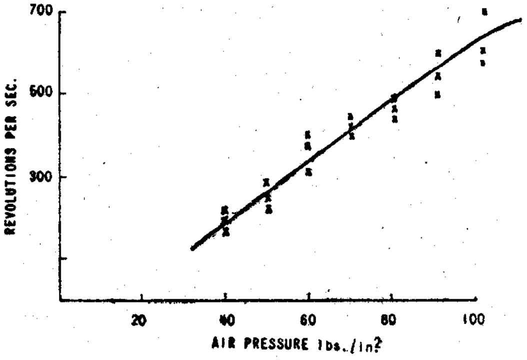


Fig. 8—Pressure speed characteristic of turbine

THE TECHOMETER

Event displacements D_x and D_y and from these the event velocities are to be interpreted from the exposed film. Had the mirror not been moving the relations would be, from figure 2

$$D_x = md_x$$

$$D_y = md_y$$

where m is the magnification. However, the rotating mirror imposes a sweep velocity on the image and the above set of relations in terms of velocities can be written as

$$V_x = mv_x$$

$$V_y = mv_y \pm v \text{ sweep}$$

In general both components V_x & V_y are present and the image on the film is a curved trace. Edles and Whittaker's[3] treatment applies. v sweep has to be known as accuratley as possible or in other words the r.p.s. of the mirror on the turbine shaft must be known at the time of recording the event.

A compressed air turbine has small torque and a mechanical counter tends to load it. A transistorised optical tachometer is, therefore, used. A small aperture in a disc mounted at the hind end of the turbine spindle allows light from a source to fall on a photo-transistor once every revolution. The net amount of light falling per second on the photo-transistor naturally depends on the number of times per second the light pulse is allowed by the aperture in the disc, that is, it depends on the speed of rotation of the disc for a given size of the aperture and given intensity of light. The intermittent photo voltage developed by the photo transistor is amplified and integrated. This integrated value is read on a micro-voltmeter. The circuit for this is shown in Fig. 9. The tachometer requires pre-calibration. This is done using a scaler and a stop watch. Since the voltage developed by the photo-transistor also depends on the intensity of light falling on it, the calibration requires frequent check up. It is being considered to provide a constant voltage supply instead of the dry cells to avoid the variation in the calibration over longer periods. In any case the tachometer, though a compact and rugged instrument, is not very precise and is subject to temperature variation. It gives revolution counts with an error of

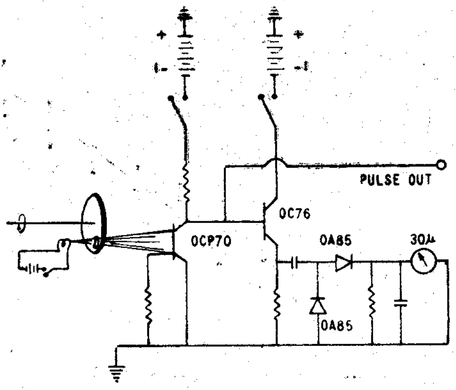


Fig. 9—Circuit for transistorised optical tachometer

3 to 4%. Since the film length is 200 mm, the variation in total event time T as determined from the trace covering the entire length of the film can be ·005 sec. to ·0048 sec. that is about ·2 millisec. or less.

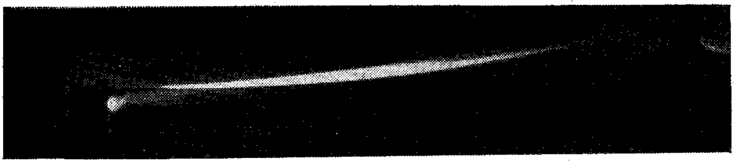


Fig. 10—Photograph of an exploding wire

The 'pulse-out' point is connected to a synchroniser through a press switch. Then if the position of the aperture on the tachometer disc is so adjusted that a light pulse passes just when the mirror has moved out of the film region (beyond 45°) a time $3T$ must elapse before the event is triggered. Thus the synchronizer is to be set for this delay time. A shorter delay can, of course, be used by advancing the mirror on the turbine shaft. Larger delay time ($T+3T$) can also be used. For time larger than this, the succeeding voltage pulse from the tachometer is also received by the synchronizer and causes complication. A photograph of exploding wires, taken in this manner, is shown in Fig. 10 and the camera is shown in Fig. 11.

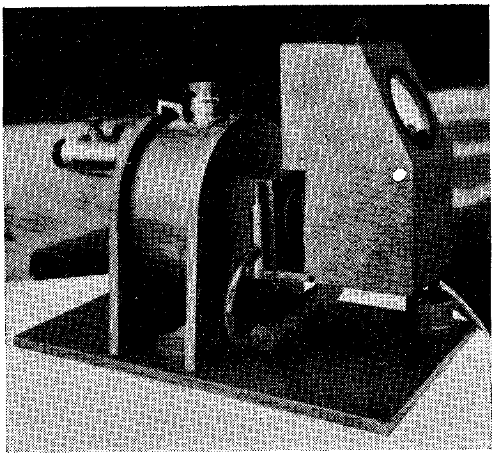


Fig. 11—Camera

ACKNOWLEDGEMENT

The author is indebted to Dr. D. S. Kothari, the then Scientific Adviser whose keen interest was a constant source of encouragement to continue the work inspite of so many odds.

The suggestion for a transistorised tachometer came from Shri N. S. Bhalla of the Rare Minerals Divisions of the A.E.C. It is acknowledged with thanks.

Author is also thankful to the industrial staff of the Instruments group of the Defence Science Laboratory who spared no effort in the fabrication of this camera.

REFERENCES

1. Naslin, P., *La Nature*, **3265** (1957), 161.
2. Naslin P., *Proc. Third International Congress on High Speed Photography*, Butterworths, (1957).
3. Edles, H., & Whittaker, D., *J. Sci. Instrum.* **32** (1955), 103.
4. Beams, J.W., Linke, F.W. & Sommer, P., *Rev. Sci. Instrum.*, **9** (1938), 413.
5. Beams, J.W., *Rev. Sci. Instrum.*, **1** (1930), 670.
6. Ford T.F., Ramsdell, G.A. & Klepp, L.W., *J. Phys. Chem.* **59** (1955), 922.
7. Buck, W.E., *Rev. Sci. Instrum.*, **25** (1954), 115.