Model 200 Reflecting-Optics Sweep Camera

PAPER G—5

By THURE ANDERSON

A sweep-image camera uses reflecting optics to achieve certain preselected performance characteristics: (1) high writing speed (30 to 60 mm/μsec); (2) f-number to produce image densities generally accepted on existing sweep cameras, f/8; (3) resolution compatible with film generally used, 70 lines/mm; (4) absence of chromatic aberration; and (5) rugged compactness. Two basic designs are discussed: one is a basic camera for infinity or near infinity use, having three reflecting components, an off-axis parabolic mirror objective, a flat "diagonal" mirror and the rotating mirror; the other is a basic camera with external, independent objective, or telescope, for any distance, using spherical mirror off-axis with cylindrically corrected diagonal and rotating mirror.

A three-sided rotating mirror, with high length-to-diameter ratio is used, permitting a design speed of 32,000 rps, maximum. The stationary mirrors conform to the same aspect ratio as the rotor (approx. 6 : 1). The camera body is explosion proof and easily adapted to vacuum operation. 16mm film is used. The film support deviates from a true circle to provide constant overall optical path length. The camera is continuous "writing," each face "writing" 240° with overlap to permit continuity with the following face, and thus need for synchronization with the recorded event is eliminated.

High-speed sweep-image cameras have found a permanent acceptance as an instrument for recording rapid transient events. Especially was this true in the field of nuclear explosions, where the greatest impetus was provided for development work. It was here also that the greatest emphasis was placed on speed. The base of interest and application has since broadened to include among others such fields as ballistics, solid-state physics, rapid arc discharges, and time-based spectroscopy.

General Design Considerations

A study of existing sweep cameras was made four years ago, in an attempt to extend the parameters of performance with emphasis on speed, *f*-number, and resolution. Complete freedom from chromatic aberration was also desired, thereby improving resolution and ideally fitting the requirements for time-based spectroscopy. The use of mirror optics, besides fulfilling this last requirement, also enabled achievement of a better *f*-number and reduced the cost of design and construction of the optical components.

A writing speed comparable to that achieved by modern oscilloscopes was also deemed desirable. Since writing speed varies as the product of the angular mirror velocity and length of writing arm, this quantity has to be compromised with an *f*-number that will admit enough light to expose the film at the desired writing speed. This compromise then will be determined by the intended application for the camera. The *f*-number will be proportional to the mirror area but this cannot be increased without losing rotational speed, except in one direction, namely in length. So it was this remaining frontier that was explored to the fullest. A mirror with triangular cross section, having face dimensions of $\frac{5}{16}$ by 2 in., was selected as the extreme length-to-width ratio that could possibly be used. Realizing all the problems with dynamic balancing, whirling and resonance phenomena, bearing behavior, turbine limitations, and optical considerations, the choice was obviously optimistic. There is great satisfaction in knowing that the upper limit of a problem has been investigated, because the optimum then must lie just one step below. The choice of mirror dimensions resulted in a maximum design speed of 32,000 rps.

It is obvious that an optical aperture ratio of approximately 6:1, while satisfying effective *f*-number requirement, leaves something to be desired in resolving power of the short dimension of the mirror, thereby affecting time resolution. Again the intended application must decide the compromise. For instance, in time-based spectroscopy, space resolution (wavelength) may be more important than extreme speed. In our design, which is purely experimental, provisions were made for the use of wider mirrors to suit varied applications. It should be borne in mind that a small increase in mirror width (say 25%) with resultant loss in rotor speed would, to an appreciable degree, be compensated by improved optical time resolution.

Two other considerations in the design concerning optical performances are given below.

(*1*) *Constant path length for the recording light beam:* This insures sharp focus for the entire film length. The film support was made flexible and is permanently adjusted to computed values with respect to the true mounting circles. The rectangular mirror objective is *f*/2 in the long dimension, resulting in a very shallow depth of focus, hence the constant path length is important.

(*2*) *The possibility of operating the camera under vacuum:* The camera body was made rugged with reasonably tight joints, at the same time providing an explosion-proof design.

Without going into a "hard" vacuum, substantial gains in over-all resolution can be obtained. The designing of a rotor to operate in vacuum presents a greater problem, but work is being done on its solution.

Specific Design Considerations

The first model to be constructed for a specific use anticipated a field assignment in the observation of

---

Presented on October 20, 1960, at the Fifth International Congress on High-Speed Photography in Washington, D.C., by Thure Anderson, Lawrence Radiation Laboratory, University of California, Livermore, Calif. The work reported here was done under the auspices of the U.S. Atomic Energy Commission.

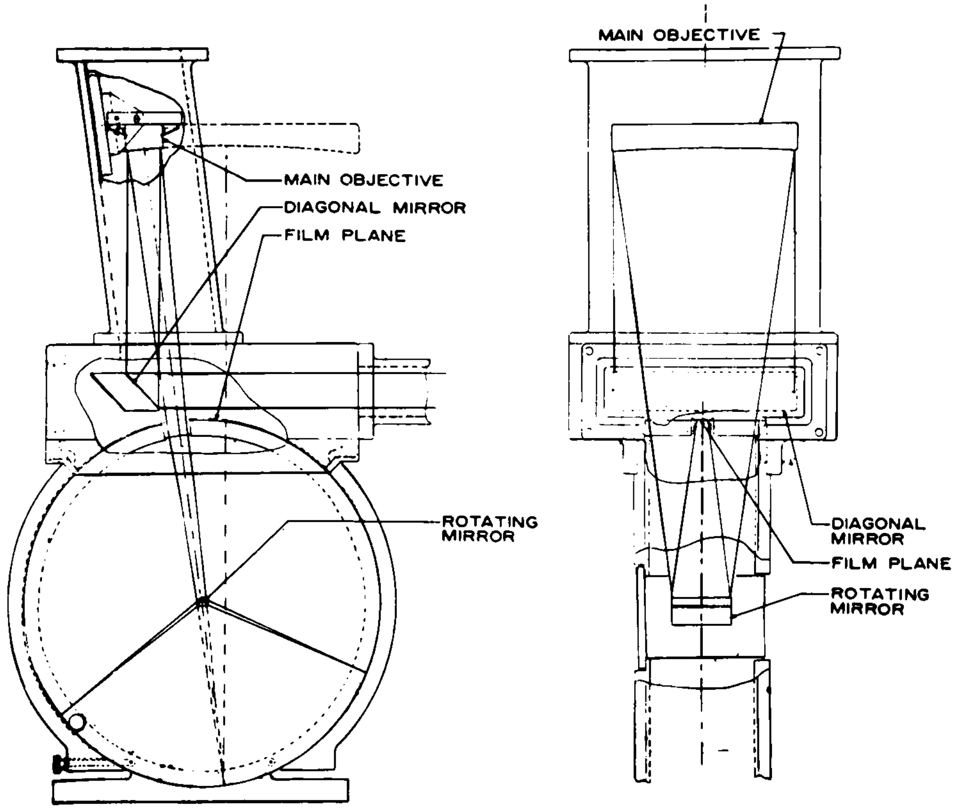

Fig. 1. Sweep camera, Model 200 (original version), using mirror optics. Designed specifically for recording, at considerable distance, sequential events, such as nuclear explosions.

sequential events taking place at large distances. Reference to Fig. 1 shows that parallel light enters the case from the right, falls on the secondary flat mirror, is reflected from the main objective (an off-axis parabolic mirror), past the film "plane" onto the rotating mirror, and is then focused at the film "plane" which extends 240° about the rotor axis as a center. The converging light beam passes through an aperture on each side of the film support before reaching the rotating mirror. An unavoidable obscurement occurs with consequent loss of light. This is allowed for in the design *f*-number.

The need for the intended application ceased during the development of this camera, and design changes were therefore made to increase the scope and versatility of the original model. Figure 2 shows the basic changes from the original version. This design is intended to work with an external objective to form a primary image in front of the camera, usually in coincidence with a slit. This primary image, with the slit, is then focused by the camera relay mirror, through the diagonal and rotating mirror, onto the film "plane" at or near unit magnification.

A glance at the optical layout (Fig. 2) makes it obvious that a spherical mirror is indicated to work at or near unit magnification. The necessary angle of tilt (approximately 3.5°) introduces off-axis aberration, which, of course, was not inherent in the original design where an off-axis parabola neatly solved the problem. One finds many applications for mirror objectives, used off-axis, such as schlieren wind-tunnel systems, gas spectroscopy, etc., but usually all the light is collimated through a slit, and desired resolution is in one dimension only, sagittal or tangential. What apparently has not been realized is that, if a correction could be introduced, even the one-dimensional image would be appreciably enhanced in quality. A careful study of the problem was made and a satisfactory solution was found.

Since most applications of mirror objectives require a flat mirror (diagonal) or prism in the system, a slight cylindrical correction of the flat surface will in most cases offer a convenient and completely satisfactory correction. Elliptically compensated mirrors have also been used but are expensive and difficult to produce. It is com-

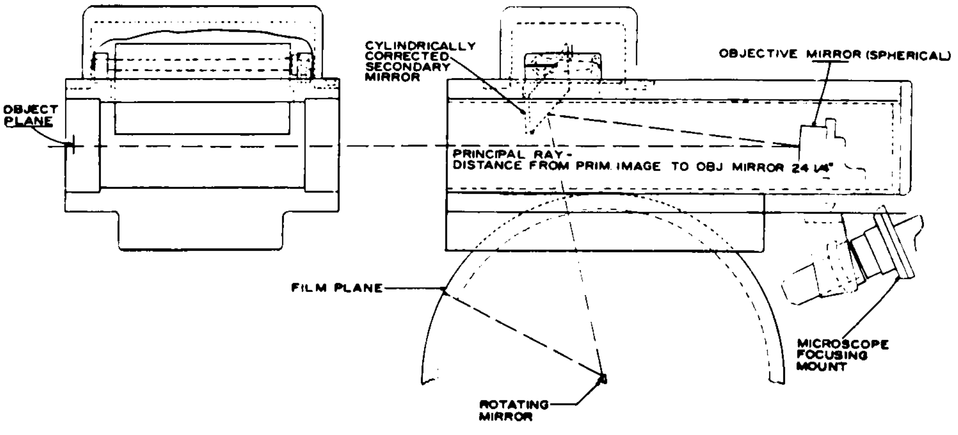

Fig. 2. Later version of Model 200 Sweep Camera, incorporating changes in the optics designed to make the camera more versatile and extend its usefulness. Included in the revised experimental model is a spherical mirror and a cylindrically corrected secondary mirror.

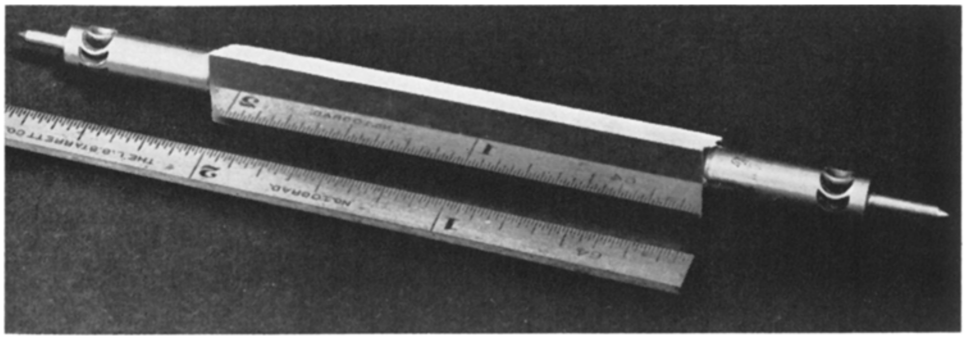

Fig. 3. Three-sided rotating mirror. Diameter of journal is only (approximately) 1/16 in.

paratively easy to produce perfect spheres and cylinders by classical methods. The cylindrical correction seems to work equally well for spherical and parabolic mirrors.

In our case (Fig. 2), the total reflecting angle was approximately 7°. The proper cylindrical correction was established empirically by warping a flat mirror in a very accurate fixture until maximum resolution was obtained. This occurs when the tangential and sagittal images come into perfect coincidence. The correction was then observed with an optical flat and expressed as "n" fringes across the short dimension of the mirror. The amount of cylindricity required in our design (Fig. 2) was twelve fringes of convexity in the short dimension (1 in.) of the diagonal mirror. The correction is extremely effective and the amount of cylindricity is very important. The effectiveness of the correction is such that, in this design, without the correction no recognizable image is produced. With the correction, up to 200 lines/mm can be resolved in the space direction (across the film). This is static resolution after a total of three reflections through the camera, and approaches Rayleigh's limit. Compensation can be maximized by slightly changing the reflected angle at the spherical mirror, thereby decreasing or increasing the need for correction. The distance from the cylinder to the spherical mirror is also very important: the effectiveness varying inversely as the square of that distance. The magnitude of correction was also computed, confirming the empirical data.

A complete study of this method of correcting for off-axis aberration, evaluating coma and secondary aberration, has not been made. A few tests have been made with spherical and parabolic mirrors, working off-axis, and no appreciable difference was seen between the normal on-axis resolution and that produced off-axis with proper correction, provided the total angle did not exceed 14°. A notable improvement was seen when an $f/8$ paraboloid was equipped with a corrected diagonal mirror placed outside the entrance pupil of the telescope. The improvement was no doubt due to the elimination of spider diffraction caused by the usual support of a Newtonian diagonal mirror.

The Rotor Assembly

As indicated above, the rotor is three-sided with an equilateral cross section, with face areas $\frac{5}{16}$ by 2 in. The choice of the design speed of 32,000 rps was based on the tensile strength of the rotor material (approximately 250,000 psi). At speeds above 20,000 rps the previously used bucket wheels can no longer be considered practical. Buckets of the Terry turbine type are therefore milled integrally with the shaft just inside the journal section (see Fig. 3). The journal is approximately $\frac{1}{16}$ in. in diameter and runs in silver bearings with 0.0003 in. clearance. Bearing behavior is normal with negligible wear if the journals are chrome-plated and optically polished. However, the balancing of such a slender rotor is extremely difficult, and the slightest unbalance will cause whirling and excessive vibrations at the bearings. When this occurs top speed cannot be reached. While top speed has been achieved on test runs, a great deal has to be done before this can be considered an operational speed. A slightly larger diameter with some loss in top speed is contemplated. The balancing problem is due to lack of supersensitive balancing equipment. The rotor has to be operated with compressed helium gas and run in the same atmosphere, or in a vacuum. The flexibility of the rotor also makes perfect mirror flatness difficult to achieve.

Performance

Since the Model 200 sweep camera is still in the experimental stage, no attempt has been made to assign fixed and precise performance figures. The present f-number of $f/8$ can be improved considerably by widening the mirrors (up to 100%), without losing the inherent advantages of the basic design. Contingent upon an operational rotor speed of 32,000 rps, the writing speed would be 56 mm/μsec with a 6-in. writing arm. Observed static resolution is 70 lines/mm in the sweep (time) direction, 200 lines/mm in the space direction.

This paper is presented for the purpose of stimulating interest and development in the field of high-speed photography, sharing the accomplishments as well as the many remaining problems with those who are in a position to aid science in the study of rapid phenomena.

Acknowledgments: The author is indebted to the following in developing the Model 200 camera: for programmatic support and consultation, Ervin C. Woodward, and Willis C. Goss; for design of original rotating mirror assembly, Raymond E. Keyes. The support of the optical technology staff in building the prototype is gratefully acknowledged.