VFK-ÚVOJM High-Speed Framing Camera

PAPER H—5

By JAN HAMPL

A double-drum, high-speed framing camera capable of photographing fast-moving mechanical and electrical machinery for quantitative analysis produces 1304 pictures, each 5 by 8 mm on a 1850-mm length of unperforated 35mm film. The camera can record at 6000 to 42,000 frames/sec, with an aperture ratio of f/7, and resolves 80 lines/mm. Synchronization of image motion with the moving film is accomplished by rotating an inner drum carrying secondary objective lenses at the speed necessary to cause the image to move at the same velocity as the film on the outer drum.

General Description

The camera was designed and manufactured by the Meopta Optics and Fine Mechanics Research Institute at Přerov, Czechoslovakia, to meet the requirements of some research departments of the Skoda Works, particularly those working on air-blast circuit-breakers, steam turbines, high-speed machining and milling, and material testing problems. This camera ranks among the medium high-speed cameras, with respect to frequency and total number of frames.

Since the customer had not required cine projection but had required a good resolving power of individual frames capable of giving enlarged pictures, the camera was designed as a drum-type apparatus with a rotating film and appropriate photographic objectives. These, totaling 1200 in number, are arranged in a ring of four bands. See Figs. 1 and 2.

A Belar objective (F, 210mm; relative aperture, *f*/4.5) was chosen to operate as main (collimating) objective. In addition, the camera is provided with two supplementary collimating lens systems, one with a focal length of 500 mm for taking pictures at a distance from one meter to ∞ (measured from the front surface of the objective), the other with a focal length of 83 mm for taking macropictures with a magnification as high as 10 × between the entrance stop and the object. This is a high-speed objective with a relative aperture of *f*/0.8.

The relative aperture of the camera is *f*/3.8. It depends on the relative apertures of the secondary lenses which are laid out in a quadruple circle on the circumference of the drum; but owing to the incorporation of a shuttering stop in the form of a slit on the face of the lens (see Fig. 9 below) it is further reduced to *f*/7 (which, however, is still a considerable speed, where ultrarapid cameras are concerned).

The frames, 5 by 8 mm, are arranged in four bands (Fig. 11). The total number of frames for one run is 1304. Unperforated 35mm cinematographic film strips, 1850 mm in length are used, either black-and-white or color. The resolving power of the system amounts to 80 lines/mm. The pictures can be enlarged without difficulty to 13 by 18 cm, tolerable sharpness being maintained.

The electromagnetic camera shutter is actuated by a special electronic control unit, and is released through this control unit either manually or by an impulse provided by the studied phenomenon itself. The exposure lasts for only one revolution of the film drum. To open the shutter fully and to close it again requires a total of 1.5 millisec. The short duration of the shutter response allows full exploitation of the camera and a maximum number of fully exposed pictures.

At the maximum rate, the exposure of each individual picture lasts no more than 1/42,000 of a second. The object under study, if it has no intrinsic radiation, must be illuminated artificially. Conventional flashtubes, which can also be started off by means of the electronic control unit at the moment of the exposure, can be used to advantage for this purpose. The investigation of powerful electric discharges does not, of course, require

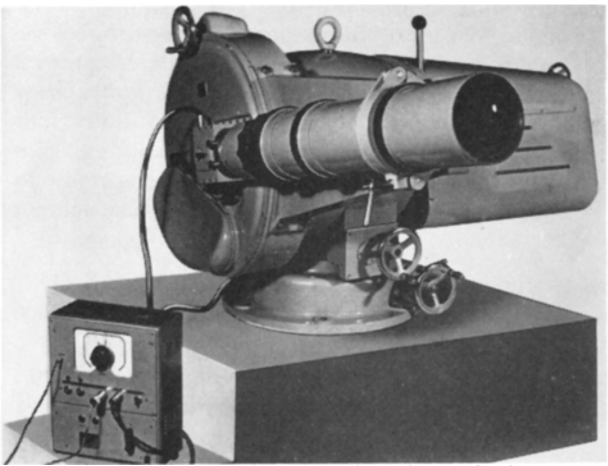
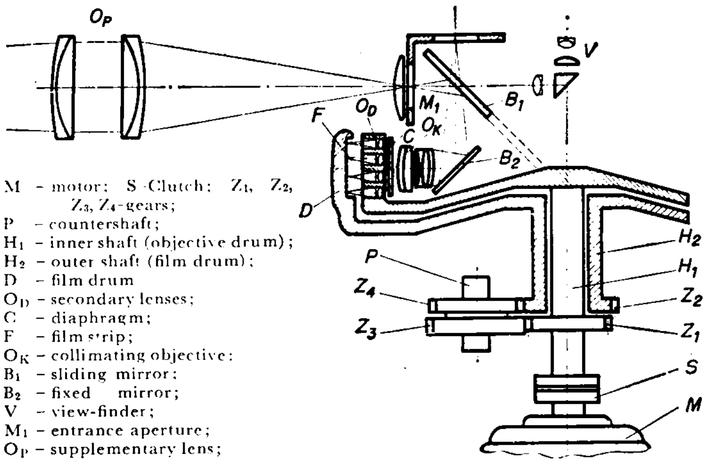


Fig. 1. General layout including triggering unit. Camera shown with a supplementary lens F = 500 mm, and a set of extension tubes.



M – motor; S-Clutch; Z_1, Z_2, Z_3, Z_4-gears;
P – countershaft;
H_1 – inner shaft (objective drum);
H_2 – outer shaft (film drum);
D – film drum
O_D – secondary lenses;
C – diaphragm;
F – film strip;
O_K – collimating objective:
B_1 – sliding mirror:
B_2 – fixed mirror;
V – view-finder;
M_1 – entrance aperture;
O_P – supplementary lens;

Fig. 2. Schematic diagram of optical and mechanical design.

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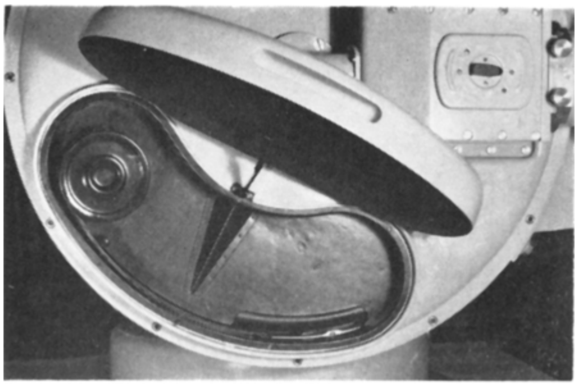

Fig. 3. Loading space of the camera. The magazine is ready for the film to be drawn into the film drum. On the top righthand side can be seen the closed aperture of the auxiliary optical system for lateral shots.

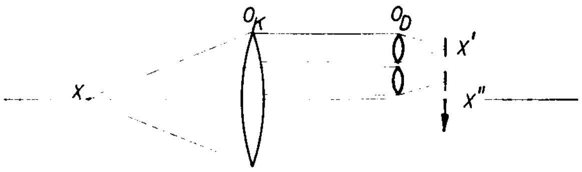

Fig. 4. Principle of optical compensation.

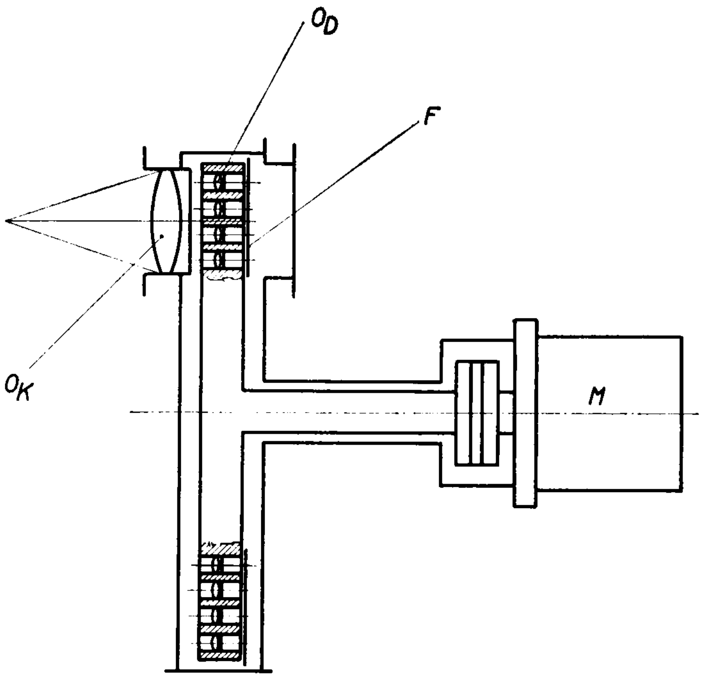

Fig. 5. Schematic drawing of simple disc-shaped high-speed camera working according to the principle shown in Fig. 4.

any additional illumination; sometimes, in fact, the brightness of the phenomenon must be reduced by means of neutral filters.

The camera is driven by a 2.2-kw commutator motor with speed variable from 300 to 2100 rpm. This permits a continuously variable picture rate from 6000 to 42,000 frames/sec, and a total exposure time for the 1304 pictures ranging from 0.2 to 0.031 sec, the latter figure referring to the maximum rate.

Before the shot is taken, the camera rotors are set in motion so as to reach the speed corresponding to the required frame rate. When this rate has been set on the control unit, it is only necessary to wait for the moment suitable for the exposure which — given the correct setting — takes place during one revolution of the film drum. In this way double exposure of the film is prevented.

The camera is movable about the vertical and horizontal axes by two hand-operated wheels. Another hand-operated wheel connected with a friction device for driving the rotors by hand is used for loading the camera.

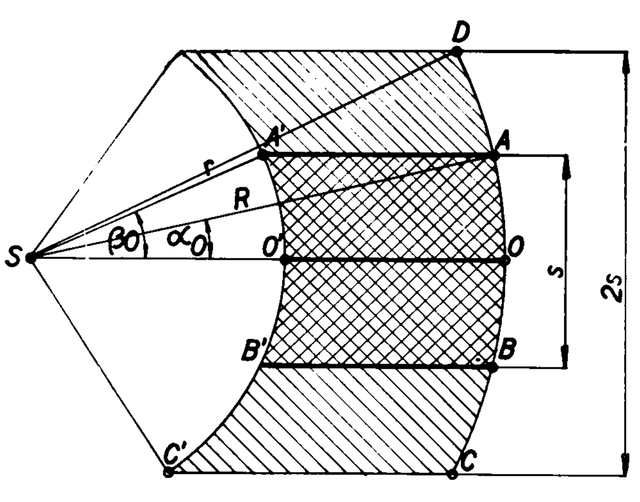

Fig. 6. The condition of image and film synchronization.

The film is put into a specially shaped magazine which allows daylight loading (Fig. 3); the end of the film is gripped in a notch in the drum; and the film is drawn into its bed by manual rotation of the drum. The camera is then ready for shooting. The film is kept in position by centrifugal force. (At maximum speed the acceleration is 1200 g.)

Design Principles

The principle of the optical compensation of the camera is shown in Fig. 4. A stationary object X or its optical image is placed in the focal plane of the main (collimating) objective O_K. The rays emanating from the test object are transformed by the objective into a parallel beam of light. From this beam the secondary lenses O_D pick up their imaging rays. Even if the secondary objectives move across the parallel beam of light, the images X', X'' remain stationary with respect to the (moving) optic axes of these objectives. It is, however, necessary that the optic axes of the objectives O_D be kept parallel with the axis of the main objective O_K. (More generally this requirement applies to the line joining the second principal point of the secondary objective with the frame center.) With a disc-shaped camera and the rays traveling parallel to the disc axis, this would be very easily achieved (Fig. 5). However, the difficulty lies in providing and loading the flat film F in the form of an annulus. For the use of orthodox strip film it is, therefore, necessary to replace this axial principle by the radial solution. Optical compensation is secured here by dividing the system into two drums, one of which (the interior one) carries the secondary objectives O_D while the other (the outer one) carries the film pressed by the centrifugal force into the film bed. If the circumferential velocity of the principal points of the secondary objectives O_D is equal to the velocity of the film surface, then — within certain limits — the above condition for "unblurred" photography is achieved.

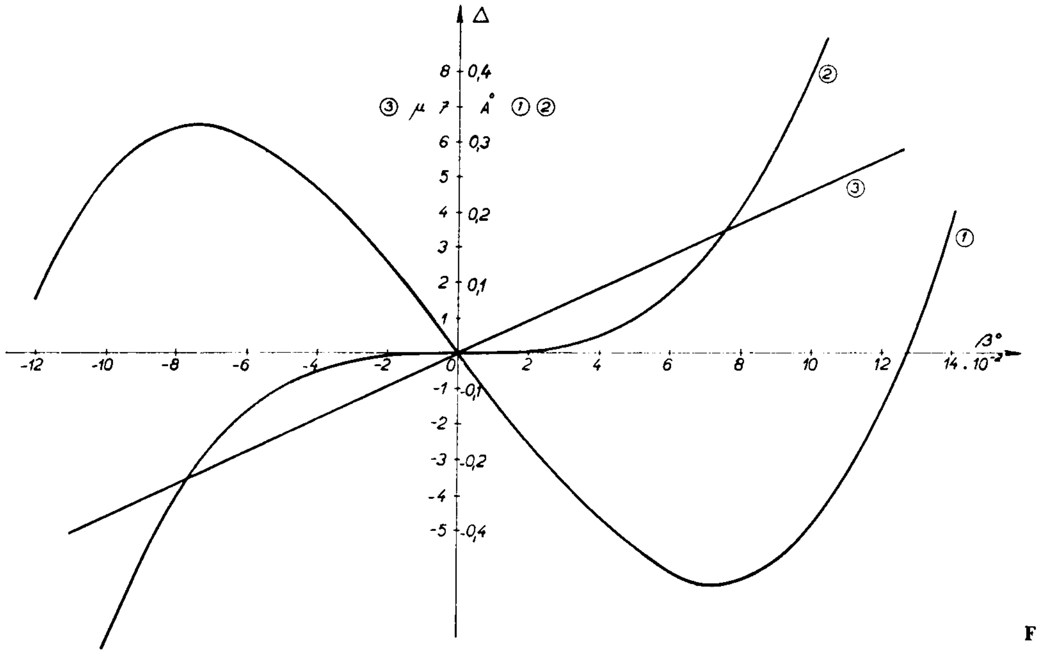

Fig. 7. Aberration analysis.

To prove this, consider a line AA' in Fig. 6 parallel at the moment $t = 0$ to the optic axis of the main objective. The height difference Δ_0 between A and A' is zero. Therefore

$$\Delta_0 \equiv R \sin \alpha_0 - r \sin \beta_0 = 0. \tag{1}$$

Denoting the angular velocities of the radii R,r by ω_α, ω_β, respectively, the height difference Δ of the right-angle triangles at a later moment t is given by

$$\Delta \equiv R \sin \alpha - r \sin \beta = R \sin (\alpha_0 - \omega_\alpha t) - r \sin (\beta_0 - \omega_\beta t), \tag{2}$$

where we assume that the rotation takes place in the negative direction. When the radius vector R is crossing the main optic axis

$$\alpha \equiv \alpha_0 - \omega_\alpha t = 0;$$

$$\text{so that } \Delta = -r \sin \beta = -r \sin \left(\beta_0 - \frac{\omega_\beta}{\omega_\alpha} \alpha_0\right). \tag{3}$$

If now the gear ratio is so designed that

$$i \equiv \frac{\omega_\alpha}{\omega_\beta} = \frac{\alpha_0}{\beta_0}, \tag{4}$$

expression (3) vanishes. For symmetry reasons parallelity is resumed in a situation, denoted in the figure by BB', the parallel positions thus being $(\pm\alpha_0, \pm\beta_0)$, $(0,0)$.

The symbol $(\pm\alpha_0, \pm\beta_0)$ represents parallelity, if according to (1)

$$\frac{\sin \alpha_0}{\sin \beta_0} = \frac{r}{R}. \tag{5}$$

Combining (4) and (5) and denoting $(\sin x)/x \equiv S(x)$, the condition of restored parallelity can be written as

$$\frac{S(\alpha_0)}{S(\beta_0)} = \frac{\nu_\beta}{\nu_\alpha}, \tag{6}$$

where ν_α, ν_β are the circumferential velocities of the radii R,r, respectively.

For small angles α,β the condition (6) reduces to equality of circumferential velocities, as stated above.

However, it is interesting to have a detailed qualitative view of the aberration from parallelity. Choosing in (2), β as the independent variable, one gets

$$\Delta = R \sin i\beta - r \sin \beta = (iR - r)\beta + \frac{1}{6}(r - i^3 R)\beta^3 \tag{7}$$

where the expansion is sufficient for the range of angles under consideration.

Confining ourselves to the vicinity of the condition $i = (r/R)$, where $r<R$, makes the second expansion coefficient positive and the results may be classified according to the sign of the first term.

The curves in Fig. 7 show the three types of cases one can meet in compensating the optical system by adjusting the angular velocities of the two drums. All concern the given camera with $r = 264$, $R = 290$ mm $[(r/R) =$

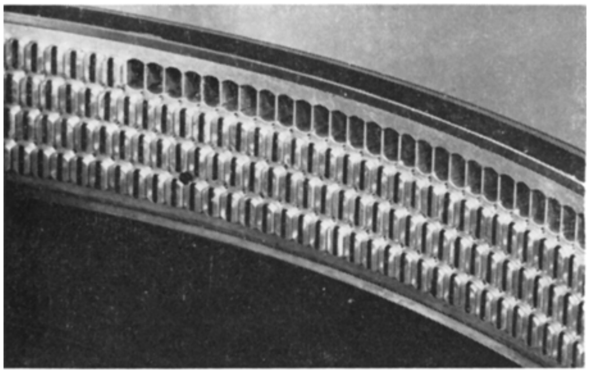

Fig. 8. Circular bank of objectives on the circumference of the inner drum.

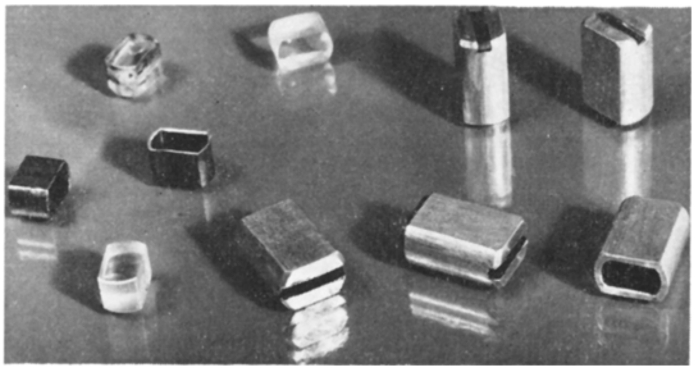

Fig. 9. Secondary objectives, showing shuttering slits.

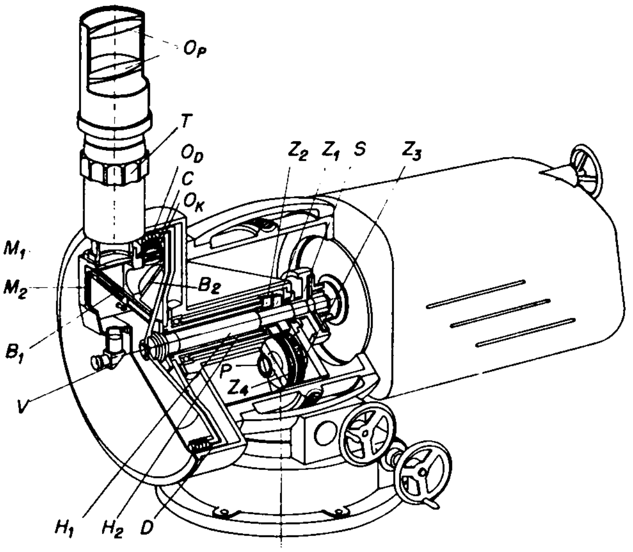

Fig. 10. Cutaway view of the VFK-ÚVOJM High-Speed Camera; T – focusing ring, M_1, M_2 – entrance apertures, other keys as in Fig. 2.

0.9103448] and a field angle 0.16°. Curve 1, displaying three zero points with two relative maxima in between, corresponds to $i = 0.9103447$. The number of decimal digits involved and the order of magnitude of Δ shown in the Fig. 7 render this case purely fictitious as far as mechanics is concerned. The same holds true of curve 2, for which $i = (r/R)$ exactly. These examples are given only to illustrate the qualitative difference between $i \lessgtr (r/R)$. Since Δ is then by many orders below the resolving power, there is no practical sense in computing the distribution of blurring across the frame according to the curves 1 and 2, although in other cases the choice of i might prove to be of decisive influence.

Generally it may be stated that the above-mentioned condition of equal circumferential velocities on axis is represented by the curve of the type 2, which means that maximum blurring is at the point furthest from the axis.

Every theoretical gear ratio can of course be realized only within certain limits. In the present camera this ratio is 0.9194000, leading to curve 3, with Δ of the order of microns. Total blurring is equal to twice the maximum positive value of Δ, i.e. in the given case 15 microns, which is just below the resolving power of normal 35mm negative films to be used. Moreover, it should be noted that this maximum blurring is recorded

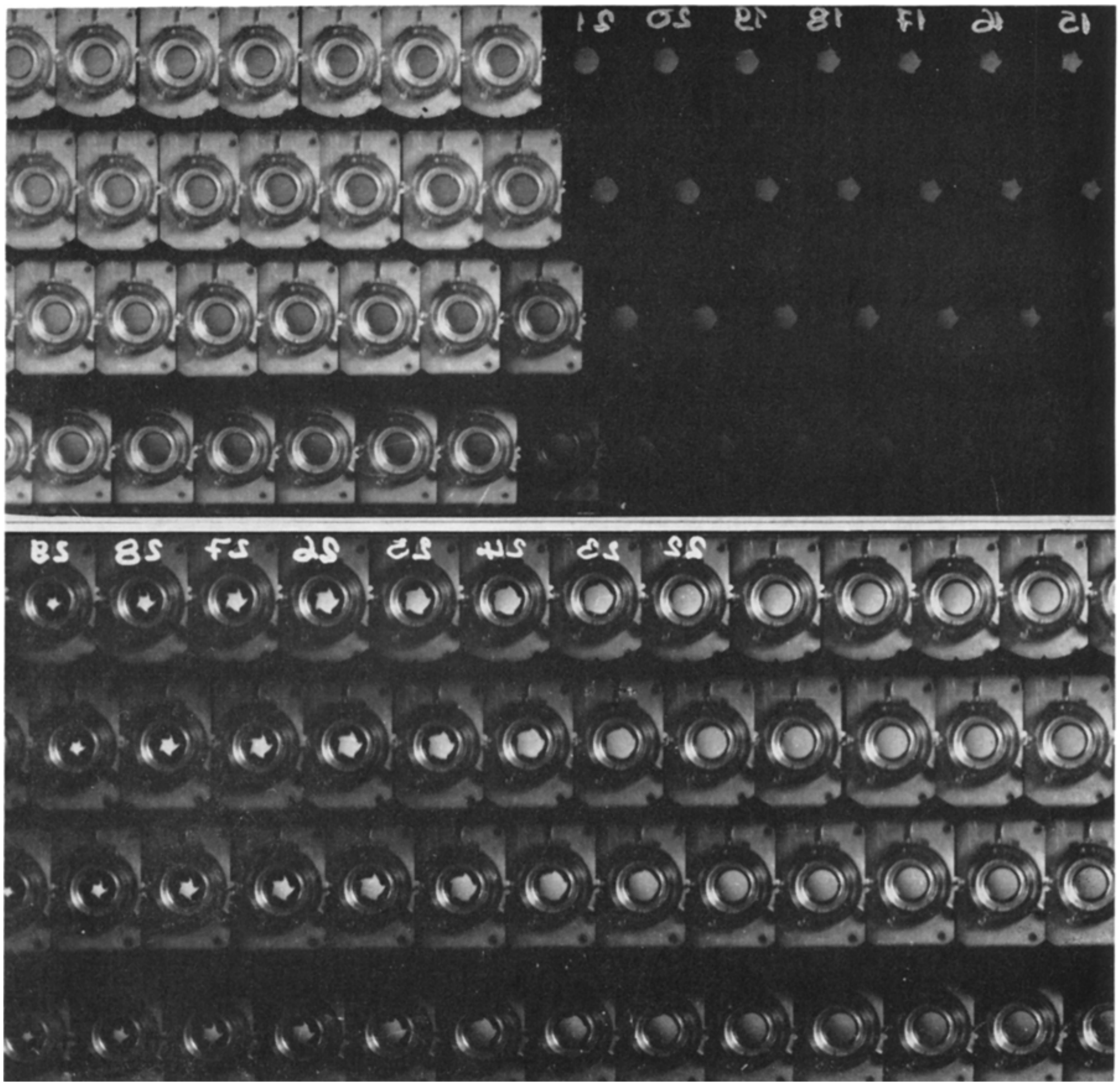

Fig. 11. Example of results obtained in the shutter tests.

Fig. 12. A bulb being broken by a steel ball.

with reduced weight since with equal widths of the main and exposure slits, maximum exposure effectiveness is concentrated near the value $\beta = 0$. Practical tests verified a resolving power of 80 lines/mm, as already stated.

The analysis just given has established the condition of equal circumferential velocities as a reasonable theorem and indicated the tolerance for mechanical construction.

The necessity of satisfying the more general condition (4) would probably occur with small drums carrying relatively large objectives.*

The diaphragm C in Fig. 2 with the exposure slit is arranged in the space between the collimating objective and the secondary objectives. This slit is covered by the plate of the electromagnetically controlled shutter. The plate opens the exposure slit in response to a pulse from the electronic control unit. During the exposure the circle of objectives turns at the gear ratio "i" so that some objectives operate twice during one shot. The number of pictures taken thus increases to 1304. This more effective utilization of the secondary objectives is a further advantage of the indicated solution.

In order to keep the size of the objective drum within reasonable limits the secondary objectives have been arranged stepwise in four staggered bands (Fig. 8). The time sequence of the pictures is such that from the frame in the first band we pass to the second, third and fourth bands, successively, and then for the fifth frame back to the first band, in a position adjacent to the first frame.

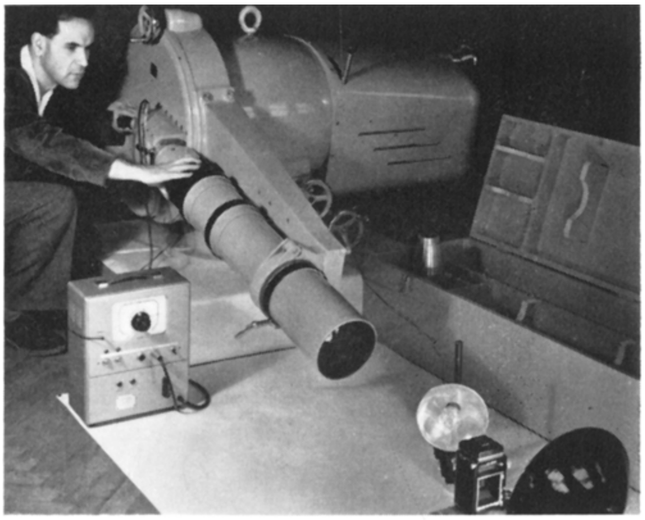

Fig. 13. The camera set up to record the operation of a shutter.

In order to achieve a sufficiently short exposure and unblurred images even with high-velocity phenomena, the diaphragm of the secondary objectives is in the form of a rectangular slit (Fig. 9) similar to the main exposure slit.

The isometric drawing in Fig. 10 shows the layout of the rotors in the camera body, as well as the position of the shafts and gears. The inner shaft H_1 is connected with the motor (not visible in the figure) through the clutch S. The outer hollow shaft H_2 is driven from the shaft H_1 through gears Z_1–Z_4.

On the face of the camera a mirror case with the sliding mirror B_1 is shown. The fixed inner mirror B_2 and the collimating objective O_K are also shown. The mirror case is part of the viewfinder system. It has an aperture which is shielded in the axial direction by the movable mirror. After removing this mirror, pictures can be taken from a picture tube, etc., with the test object placed directly on the stop of the side aperture. This aperture may also be used for projecting an auxiliary time base for pictures taken in the normal way.

The rotors were designed to avoid critical resonant frequencies, so that pictures can be taken within the whole range of 6000 to 42,000 frames/sec without running the risk of excessive vibrations.

Conclusion

Before the camera was delivered to the customer, a number of successful tests had been carried out. (Some specimen pictures are shown in Figs. 11 and 12.) The operational tests performed at the Meopta Works, Přerov, Czechoslovakia, were used for checking the shutter exposure times of some photographic cameras (Fig. 13). Valuable information on their operation was obtained on this occasion.

Acknowledgment: Thanks are due to V. Smejkal, chief designer, for working out the optical principle of the camera and to A. Vrba, who is responsible for the electronic unit.

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* The idea of moving secondary objectives across a main aperture may be regarded as classical. It has been used in practice, e.g. with the high-speed camera of the French MGD Company (Brit. Pat. 630,912). The optical compensation is there accomplished in the following way: the main objective does not act as a collimator, but it projects the picture into a plane, containing the axis of rotation of the drum. The small secondary objectives had to be mounted with their optic axes intersecting in one common point on the axis of rotation. This seems to complicate manufacture and adjustment. The idea embarked upon in the present work has proved simple to realize and reliable in operation.