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New Fast-Opening, Large-Aperture Shutter for High-Speed Photography*

E. C. Cassidy and D. H. Tsai

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A fast-opening, large-aperture, high-transmittance shutter has been developed. This shutter consists essentially of a metallic foil in a capacitor discharge circuit. The opening action is obtained when the foil is buckled and compressed laterally by the electromagnetic forces which accompany the heavy surge current through the circuit, during a transient discharge. A shutter made up of two foils in a loop arrangement may be opened to an area 1 inch × 3 inches in less than 45 microseconds. Some of the factors affecting the design and operation of the shutter are briefly discussed. These factors include the electrical energy input to the foil, the circuit parameters, and the materials and the size of the foil. Some experimental results are also given.

1. Introduction

In recent years a number of high speed photographic shutters have been developed (see for example, references [1] [1] through [6]). Of these, the Kerr-cell and Faraday type shutters [1,2] both open and close in the submicrosecond range. They are, however, characterized by poor light transmission. Reference [4] describes a shutter which opens and closes a 1.6 mm slit in about 15 μsec. References [5] and [6] are closing shutters which require 20 to 30 μsec to close. This paper describes a fast-opening, large aperture, high transmittance shutter. The shutter consists of a piece of metallic foil clamped between two electrodes in a capacitor discharge circuit. The foil is placed in front of a camera so that the camera lens is completely covered. When a heavy current is passed through the foil during the discharge of the capacitor, each current filament in the foil reacts with the magnetic field set up by the other current filaments. The direction of the force is such that the filaments are drawn together [7]. As a result, the edges of the foil are compressed toward the center filament, and the fast-opening action is achieved.

An improved arrangement consists of two foils mounted side by side in the same plane (but insulated from each other along their common edge) and clamped to a common conductor at the top and to two electrodes at the bottom. The foils thus form the two arms of a loop circuit. When current is passed through the foils, each foil is compressed by the electromagnetic forces described above, and, in addition, each foil is repelled by the other because they carry current in opposite directions [7]. The opening action is therefore faster.

Typically, a shutter with foils in a loop arrangement opens to an area 1 in. × 3 in. in less than 45 μsec. The initiation of the opening action may be controlled to within 1 μsec. When this shutter is used in conjunction with a high-speed camera and a suitable closing shutter, it gives precise control of the initiation and duration of an exposure, and permits photographic observation of any portion of a high speed event with a high percent of light transmittance.

2. Experiments

Experiments have been made to test the performance of several shutters of both the single- and the looped-foil type with foils of different materials and dimensions. Figure 1 is a schematic drawing of the discharge circuit with a looped-foil shutter. In this model, the foils were mounted on opposite sides of a thin piece of transparent plastic. The foils overlapped slightly in order to prevent the passage of light at the center. The plastic piece served to support the clamps at the top and the bottom, and to insulate the two bottom clamps (and the foils) from one another. The clamps were made rather massive in order to reduce distortion when tightened, and to provide good electrical contact with the foils.

The shutter assembly was installed in series with a high-voltage capacitor and a spark gap which served as a switch [8]. The capacitor was charged by means of a high voltage power supply. The spark gap was fired by means of a thyratron trigger circuit which supplied a high-voltage pulse to break down the spark gap. With this setup, the initiation of the discharge could be controlled to within 1 μsec. The duration of the discharge, for the foils tested, ranged from about 10 μsec to about 50 μsec. The motion of the foils due to the discharge was observed by means of a high-speed framing camera, focused on the foils.

Figures 2a and 2b show a single-foil shutter before and after the passage of current. With an aluminum foil, 1 in.×3 in.×0.0005 in. thick, it was found that the width could be compressed from 1 in. to ⅛ in. in about 100 μsec.

Figure 3 shows the experimental apparatus with two 2 in.×3 in.×0.0005 in. aluminum foils installed in the loop arrangement. In this setup, the foil

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[1] Figures in brackets indicate the literature references at the end of this paper.

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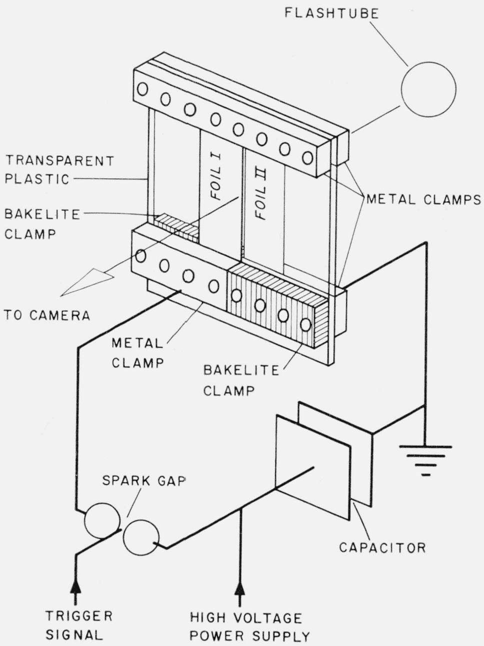

FIGURE 1. *Schematic drawing of the discharge circuit with a looped-foil shutter.*

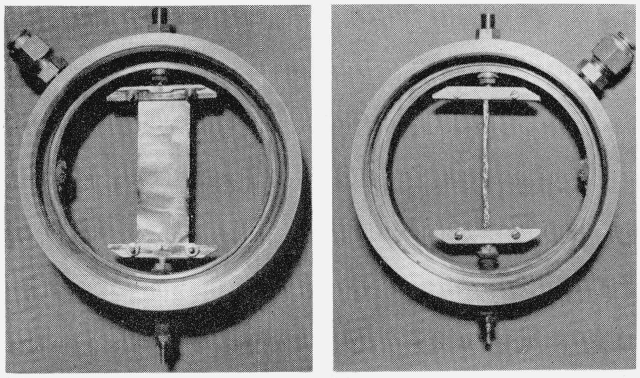

FIGURE 2. *A single foil shutter before discharge (a), after discharge (b).*

holder and the spark gap assembly were mounted on a 15 μf, 20 kv, energy storage capacitor. The opening action of a shutter of this design, with two aluminum foils (1 in.$\times$3 in.$\times$0.001 in.), is shown by the framing camera record in figure 4. Here the framing camera was focused on the foils, and the opening action was silhouetted by backlighting the foils with a flashtube. This particular shutter opened to a 1 in. $\times$ 3 in. area in about 50 μsec.

3. Results and Discussion

The opening action of the shutter (the motion of the foils) is controlled by the magnitude and duration of the electromagnetic forces, and by the mass and stiffness of the foil. The rather complex problems of solving the equation of motion for the foil and of optimizing the speed of the opening action were not undertaken in the present investigation. However, the qualitative effects of some of the design and operating parameters on the opening of the shutter were examined in an effort to determine conditions of more favorable operation. In the following paragraphs, the results of this investigation are briefly discussed, and some typical experimental results are presented.

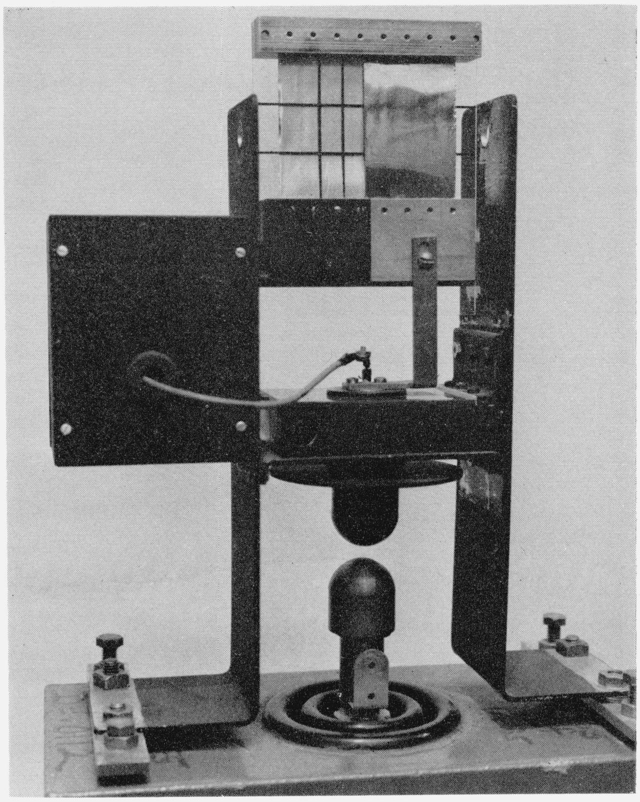

FIGURE 3. *A looped-foil shutter (before discharge) installed in the experimental setup.*

Optimum energy input—The speed of the opening action of the shutter may be increased by increasing the current through the foil [7]. However, with a given foil and discharge circuit, the maximum speed of the action is limited by two practical considerations: (1) the total electrical energy input to the foil must not be so high as to cause combustion of the foil,[2] because the flash from the combustion which is sometimes accompanied by an arc discharge would expose the film in the camera; (2) the electromagnetic forces at any instant should not be so high as to cause excessive stresses in the foil, because this could shatter the foil and interrupt the current path, and consequently reduce the driving electromagnetic forces. These considerations, therefore, determine the "optimum" energy input to a foil.

The "optimum" energy input depends primarily on the thermochemical and the mechanical (stress-

[2] All of the energy input goes into heating of the filaments because the heat loss during the disharge is negligible.

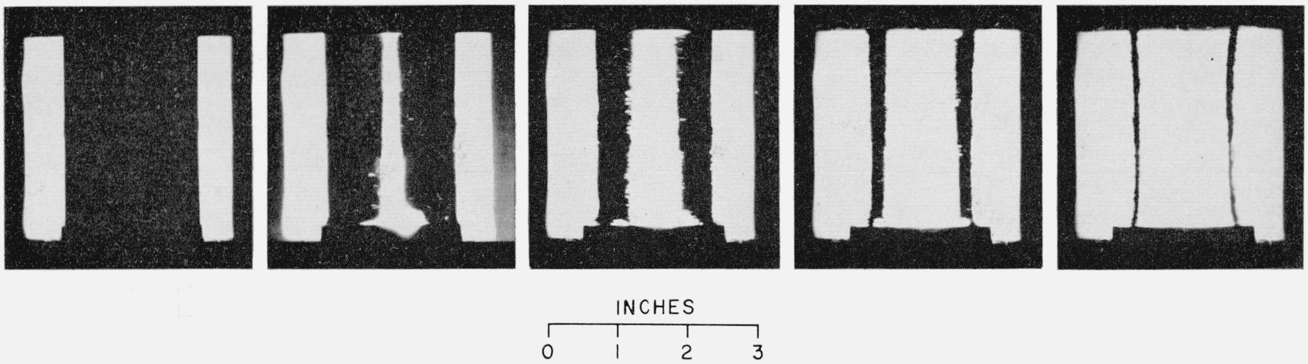

FIGURE 4. *Opening action of a looped-foil shutter (20 μsec between frames).*

strain relationship) properties of the foil material. For a given foil the "optimum" energy level may be obtained by a trial-and-error method, by adjustment of the initial energy stored in the capacitor. Experience has shown that for a given material the "optimum" energy (initial stored energy) per unit mass of foil remained approximately constant. For example, experiments, with a given discharge circuit, showed that the "optimum" energies per unit mass for the copper and aluminum foil used were approximately 4.7×10^5 j/lb and 9.9×10^5 j/lb, respectively. It was also found, of three materials tested (copper, aluminum, and Monel), that copper and aluminum were limited by burning, whereas Monel was limited by shattering.

Effect of circuit parameters—The capacitance, resistance, and inductance of the circuit affect the current as well as the duration of the discharge. These parameters therefore affect the impulse to the foil and the distribution of the impulse during the discharge. The problem of obtaining the "optimum" impulse (highest force without shattering or burning, shortest discharge time) from a given level of stored energy is difficult, and a satisfactory solution was not obtained in the present investigation. However, experimental tests showed the following results, which may be of interest to one who is seeking more favorable operating conditions.

With a given foil, for which the energy input was held fixed at the "optimum" level, a change in the capacitance in the circuit had essentially no effect on the opening of the shutter over the range tested (from 15 to 30 μf). As for the resistance in the circuit, it would seem that, for faster opening action, a lower resistance would be desirable, inasmuch as a lower resistance would allow a higher current, and thus a higher electromagnetic force. However, the resistance in the shutter circuit is mainly that of the foils. If the size of the foils is kept the same, then the resistance can be changed only by changing the material (or the resistivity) of the foil. This, of course, involves a change in the "optimum" energy and in the mass (density) of the foil. To determine the effect of changing the resistance (foil materials), therefore, one must balance the effects of these concurrent changes. In the present investigation, experiments were performed with two shutters, one with copper foils and the other with aluminum foils. The dimensions of the foils in each case were 1 in. $\times$ 3 in. $\times$ 0.001 in. For the copper foils, the "optimum" stored energy was 923 j, the density was 8.9 g/cm^3, and the resistivity was 1.8×10^{-6} ohm-cm; for the aluminum foils, these values were 528, 2.7, and 2.8×10^{-6}, respectively. It was concluded, from a consideration of these changes, that the shutter with aluminum foils should open faster. The experimental results showed that this was indeed the case. The shutter with aluminum foils opened to an area 1 in. $\times$ 3 in. in about 48 μsec, while the shutter with copper foils required about 60 μsec to open to the same area. Aluminum foil is also a good choice because of its availability and low cost.

The inductance of the circuit is determined primarily by the geometry of the circuit, and is not easily adjustable in an actual experiment. The effect of inductance was therefore not investigated experimentally. However, generally speaking, a low inductance results in a high peak current and a short duration of discharge. For fast-opening action, therefore, the inductance in the circuit should be minimized. The inductance should not, however, be so low that the peak current and thus the compressive force and the mechanical stresses in the foil become excessive and cause shattering of the foil.

Effect of size of the foil—In the present work, the length of the foil was considered as fixed by the size of the camera aperture, and was not investigated. As for the thickness of the foil, some experiments were performed with aluminum foils of the same width (1 in.) but different thicknesses (0.0005 in. and 0.001 in.). The results showed that the shutter with the thicker foils opened faster. This result was expected inasmuch as the electromagnetic forces on the foil filaments are proportional to the current squared [7] (and thus to the thickness squared), while the mass per filament is directly proportional to the thickness. The stiffness is not a factor if the foil is kept thin enough to permit buckling, because after the initial buckling of the foil the stiffness is greatly reduced. It was concluded, therefore, that if the electromagnetic forces, obtained at the "optimum" energy input, are sufficient to cause the foil to buckle, then the shutter with foils of greater thickness should open faster.

The highest opening speed achieved in the experiments was obtained with the widest foils, the foils tested being plane and of three widths: 1.0, 1.5, and 2.0 in. With the 2 in. foils, in the loop arrangement, the inner edges of each foil attained an initial speed of 1.7×10^4 in./sec, and the shutter opened to an area of 1 in. $\times$ 3 in. in about 42 μsec. The 1.5 and 1.0 in. foils required 50 μsec and 57 μsec, respectively, to open to the same area. These results were also expected inasmuch as increasing the width of the foil allows a greater current, without affecting the mass per filament or the stiffness of the foil. Increasing the width should, therefore, increase the opening speed of the shutter. Another advantage of a wider foil is that the interruption of the current path, caused when the edges of the foil are torn from the clamping electrodes in the process of opening, is less significant for a wider foil. The foil should therefore be as wide as is practical with the stored energy available. Another, possibly more effective, way of increasing the width and hence the force would be to use a corrugated foil. This, however, was not done in this investigation.

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