PAPER I—1

A Modern Reflection Shadowgraph System for Use in High-Velocity Aeroballistic Ranges

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A new-type precision shadowgraph system has been developed for use in the 1000-ft Hyperballistics Range of the Naval Ordnance Laboratory. The most important feature of the new system is its unusually high efficiency in the use of the light emitted by a spark source in making a photographic exposure. This is an important advantage in illuminating systems for use in photographing high-speed phenomena mainly because it permits the making of satisfactory latent images on the photographic material with the use of light sources which are relatively much weaker than would otherwise be required. This advantage is especially valuable in the present system, since the timing of the shadowgraph depends entirely upon the time duration of the spark light source, and since the desired exposure time, of the order of 10^{-7} *sec, is more easily obtained the lower the light output requirement.*

The component of the system responsible for its high efficiency is a 48-in. diameter polished aluminum spherical reflector of 94-in. spherical radius, mounted in relation to the spark and the camera lens in such a way as to form an image of the spark within the aperture of the lens. The camera is focused on the reflector surface, and thus forms a sharp image of the shadow cast by any ballistic phenomenon which is located between the spark and the reflector at the time the spark is fired.

The present paper describes the complete system as it has developed to meet certain design requirements, as well as some of the other possible choices of component parts which were investigated during the development.

THE BALLISTIC ranges at the Naval Ordnance Laboratory are designed and equipped to provide aerodynamic motion and flow data for projectiles and missiles in free flight. Recently, a new range was added to facilitate studying larger-scale projectiles at hypersonic velocities, above 10,000 ft/sec. The pressure-controlled test section of this range, 1000 ft in length and 10 ft in diameter, facilitates the study of aerodynamic models in flight over a longer pressure-controlled range than ever before. In choosing a proper means of recording the performance of aerodynamic models in flight through the range, certain problems had to be overcome.

Design Criteria

The first problem, because of the use of extremely high velocities, was to produce sufficiently sharp images. The choice existed between using some fast shuttering action or using a light source of extremely short duration. The needed degree of shuttering action can only be obtained on cameras which tend to be bulky and quite expensive. On the other hand, light sources of short duration have a very low photographic response. This problem existed in spite of the rapid advancement in the production of films of greater sensitivity.

It was decided that it was necessary to be able to make observations anywhere in a cross-sectional area 22 in. in diameter, in the center of the range. The second problem, then, was to provide a means of covering a test area of such large dimensions. The exact coordinates of the aerodynamic model in flight had to be recovered. This necessitated the use of two cameras which could record projections of the models along axes mutually at right angles.

It was also decided that a recording station exist every 20 ft through the range. With so many stations the problem of cost was a natural one. The installation costs, maintenance costs, and operating costs had to be kept at a minimum.

Another consideration was to provide for the extraction and storage of data in a convenient manner. This meant that the methods of loading cameras and processing exposed sensitized material be kept as straightforward as possible.

With these and other considerations in mind, various existing methods of high-speed photography were investigated. The use of various high-speed cameras and schlieren systems were considered but, because of the cost involved, they were rejected. It was also decided early in the project that a direct shadowgraph system utilizing light impinging directly on the film would be impractical. This type of system would require using huge sheets of film in order to cover sufficient test area. The film would be subject to damage and fog caused by extreme changes in pressure within the range during firing, and by luminosity produced by aerodynamic models traveling at hypervelocities.

Description and Discussion of Existing System

The recording system finally selected might be called a direct reflective shadowgraph system (Fig. 1). A point light source is positioned near the center of curvature of a concave spherical specular reflector. The reflector is positioned so as to cast an image of the point source within the aperture of a camera lens which, in turn, is situated a small distance from the point source. This provides a very efficient use of the light from the point source. The camera lens is focused on the reflector surface and thus forms a sharp image of the shadow cast by any ballistic phenomenon located between the point source and the reflector.

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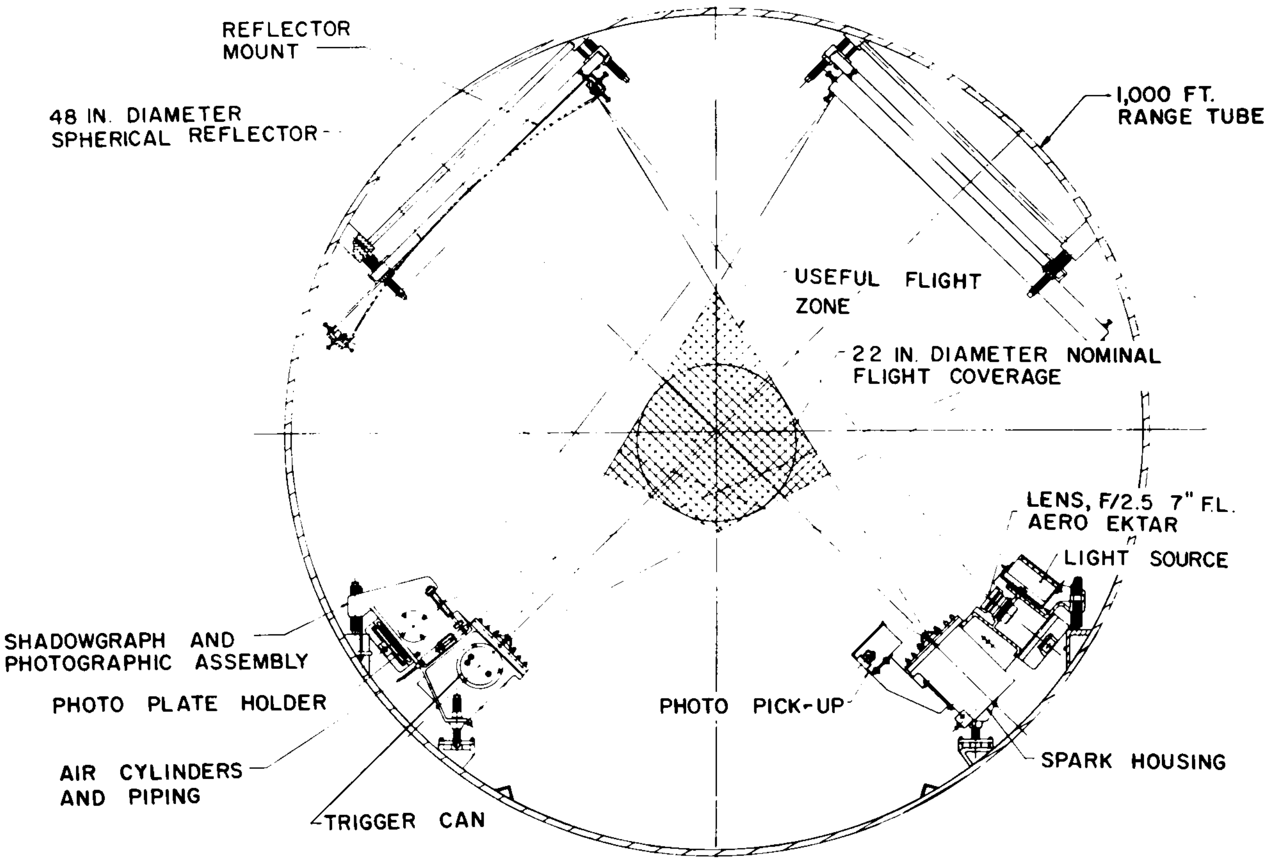

Fig. 1. Cross section of shadowgraph station.

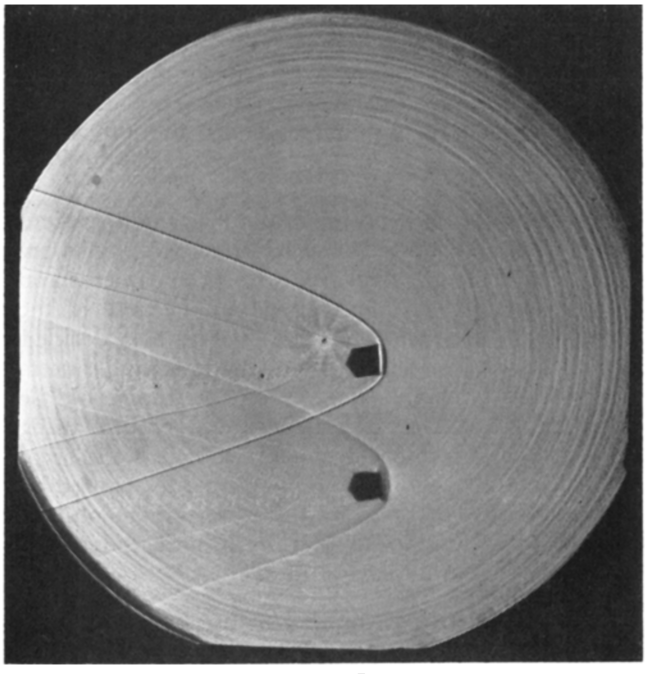

Fig. 2. Shadowgraph of missile in flight using present system.

The system, it can be seen, is similar to the well-known "Coincidence Schlieren System"* with the exception that instead of using a high-quality mirror, a special reflector is used and the schlieren knife edge is eliminated.

It is worth noting in passing that if the lens were stopped down, its aperture would operate as a circular schlieren aperture, and the whole system would act as a schlieren system, instead of as a shadowgraph system. However, the imperfections of the large reflector are too great to give acceptable schlieren pictures.

The light source and the axis of the camera lens are purposely offset a known distance in order to offset the real image from the shadow image of the model on the film. If this were not done, the luminosity of the aerodynamic model in flight would obscure all necessary detail of the model shadow image. This would not necessarily be true with a small-aperture schlieren system; but because of the inexpensive, lesser-quality reflectors used and because of the astigmatism caused by working off the reflector axis, a large aperture must be maintained at the camera lens.

An investigation was made of many types of reflecting materials before finally choosing a machined concave spherical aluminum reflector with a polished silicon oxide surface. This reflector, made by the Heyer-Schultz Corp., Cedar Grove, N.J., has a 94-in. center of curvature, and will image a 0.040-in. light source back at the camera lens with a maximum circle of confusion of 0.250 in., provided it is properly mounted. The reflector is 48 in. in diameter, thus giving a data-recording area of required dimensions. Other materials investigated were Scotchlite sheets, liquid Scotchlite, aluminized motion-picture screen material, hydro-formed aluminum reflectors, and lenticular screening.

A lenticular motion-picture screen material specially prepared by the Universal Screen Co., Clinton, Mass., was very useful. Upon investigation it was found that when a point light source was shone on this material mounted on a flat background, the light was reflected the same as it would be from a highly polished concave

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* D. W. Holder and R. J. North, "Optical methods for examining the flow in high-speed wind tunnels," NPL/AERO/300, p. 39, Mar. 1956.

cylindrical surface. It was deduced that if the material was mounted on a cylindrical surface curved in the opposite coordinate, it would act as a highly polished spherical surface; and this was found to be the case. A good substitute, then, for the polished aluminum reflector is the lenticular screen material mounted on a cylindrical surface with a center of curvature of 94 in. The cost of this lenticular material is one-tenth that of the aluminum reflector. It was not used as first choice, primarily because it is not as efficient a reflector as the aluminum. Also, it was found that with the present choice of spark light sources, the spark with the shortest duration was not intense enough when used with anything but the aluminum reflector. With the current improvement of film sensitivity, however, no doubt this reflector will ultimately be used in conjunction with, or in place of, the aluminum reflector.

Two types of spark units which have been refined at the Laboratory were chosen for light sources. The one presently being used, producing the smaller amount of light energy of the two, is a barium titanate capacitor type, with a light duration somewhat less than half a microsecond. The second, a paper capacitor type having a light duration of somewhat less than a microsecond, can be used for lower velocities. The paper capacitor-type spark has sufficient illumination for use with the lenticular screen reflector. The two sparks fit in the same pressure-proof housings and can be interchanged conveniently. Both are operated at 7000 v, d-c.

The camera component consists essentially of a 7-in., *f*/2.5 Aero Ektar lens operated at full aperture, a lens cover, and a sliding back that receives a 5 by 7-in. photographic plate holder. Both the lens cover and sliding back are operated by remote-controlled air pressure to make possible the recording of two successive aerodynamic model launchings before having to enter the pressure-controlled test area. Air pressure is used instead of electrical means to prevent electrical cross-talk which would tend to trigger the spark light sources prematurely. Both the lens and back are adjustable for focus and alignment.

The camera and spark components are supported in one rigid, cast-aluminum chassis so that the unit remains in a permanent position once installed and adjusted during a range survey. Attached to the top and bottom of one aluminum chassis at each station, and actually part of the entire unit, are a light source and photo-pickup cell which are part of a conveniently designed zero delay spark triggering system. A thin strip of red light, produced from a 24-v, $\frac{1}{2}$-amp lamp covered by a red filter, is shone on the aluminum spherical reflector. The reflector, in turn, images the light on the photo-pickup system which is composed of a 919 Phototube, a transistor amplifier, and a pressurized thyratron trigger unit. The cross section of the range at each station, then, has a red light screen over the entire data-recording area. The aerodynamic model, by passing through the light screen, reduces the intensity of light impinging on the phototube and thus triggers the sparks at that particular station. Since a photographic plate with an orthochromatic emulsion is used at the camera, the light screen has no effect on the image quality of the system. Figure 2 shows a typical picture taken of an actual aerodynamic model in flight using the system. One can see the sharp image of the shadow, and the displaced, out-of-focus real image.

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