SECTION E — Discussion: Unusual Techniques

Note: A participant's full name and address are given with the first contribution to the Discussion. Authors' full names and addresses are given with the title of each paper. For subsequent entries the addresses are omitted.

Paper E-1: Some Unconventional Methods of High-Speed Photography, *J. S. Courtney-Pratt*, Bell Telephone Laboratories, Incorporated, Murray Hill, New Jersey.

Dr. Gabriel Nahmani (Ministry of Defense, P. O. Box 7063, Hakirya, Tel-Aviv, Israel): Do internal reflections of polarized light in glass fibers affect the plane of polarization of the light?

Dr. J. S. Courtney-Pratt: No, for total internal reflection the plane of polarization is unaffected. At entrance and exit faces there could be some change of polarization, and this could affect the overall operation a little, particularly for large angles of obliquity.

Paper E-7: The Printing of Underexposed Photographs by Means of "Optical Contrasters," *Michel Cloupeau*, Laboratoire de Recherches Electroniques, Institut du Radium, Paris, France.

M. Cloupeau: The method I have described, the multiple passages of light through the film, has the advantage that you can not only print plates of improved contrast, but you can also observe them directly with improved contrast before printing.

Dr. Karl-Heinz Lohse (Aeronutronic Division, Ford Motor Company, Newport Beach, California): Can this system be used for contrast increase of color negative films?

M. Cloupeau: Theoretically, yes; but, generally, the optical densities in the three emulsions constituting the color photograph do not have the same *relative* values in an underexposed negative as in a normal negative. Because of this, the "intensified" image of the underexposed negative cannot have the same colors as those of a correctly exposed negative.

Robert E. Lewis (Beckman & Whitley, Inc., San Carlos, California): You stated that the image of a point becomes 30 microns wide after seven passes. Is this in both lateral directions?

M. Cloupeau: No, for the particular geometry of which I was speaking, this 30-micron spread corresponds to the direction of the deviation of the light rays due to the angle α. In the direction perpendicular to this, the definition can be better. It then depends on the dimensions of the source *S*.

Dr. F. L. Curzon (Department of Physics, University of British Columbia, Vancouver 8, B.C., Canada): In time-resolved spectroscopy, photographic records of low image density are extremely common. The method of intensification described could therefore be of value in facilitating the evaluation of data obtainable from such records.

Can usable records be obtained by this method in cases where the initial image contrast is so low that statistical fluctuations in the density of a series of images produced by a single event becomes important; e.g. so large that they cause fluctuation in the value of the relative image density of two spectrum lines, as determined from several individual photographs of the spectrum of a given source?

M. Cloupeau: In certain cases it is clear that the statistical fluctuations of which you speak determine the limit of the information that one can extract from an emulsion with the aid of a "contraster." Unfortunately, illumination in nearly parallel light shows up the ultimate faults of homogeneity and smoothness of the film (even in spite of immersion of the film). Along with the granularity of the film, there exists "noise" with spatial frequencies generally lower than the granularity. This parasitic effect is more or less important, depending on the quality of the film. It is this which often limits the performance of the contraster.

Dr. J. S. Courtney-Pratt: I was much impressed by M. Cloupeau's work. It may be of interest that there is some rather similar work in other laboratories, e.g. that reported by J. M. Andreas and D. H. Kelly, U.S. Patent No. 2,783,678, which describes methods of improving contrast by passing light twice through a negative. Those authors also suggest the mixing in controllable amounts of the images formed with one passage and two passages through the negative in order to give continuous control of the "gamma" over a reasonable range.

M. Cloupeau: Yes, I am acquainted with this work and with other American papers on type A contrasters. However, I do not believe that any of those systems would allow improvement in contrast corresponding to more than four passages of the light through the film.

Lincoln L. Endelman (The Martin Company, Cocoa Beach, Florida): Are we to assume that this process of intensification has been applied after a chemical intensification has been attempted? Or, is this process in lieu of a chemical process?

M. Cloupeau: The negatives, prints of which I have shown, have not been intensified by a chemical process; but one can subject negatives to such treatment before putting them in the optical contraster, with the reservation that they should not have been too much affected by diffusion and distortion. I have not yet studied the effectiveness of the various latensification processes for the underexposed region of the characteristic curve.

J. St. Thomas (RCA, Atlantic Missile Range, Cape Canaveral, Fla.): Is the amplification effect obtained essentially through apparent increase of the grain density brought about by a parallactic effect attributable to failure of the multiple light paths to achieve exact coincidence in their repeated travels?

M. Cloupeau: That depends on the particular case. For the plate faintly exposed to electrons, of which I spoke, the action of the contraster is equivalent to a multiplication of the number of the tracks of the electrons, or again to an enlargement of each opaque electron track.

An ordinary film, more nearly approximates a homogeneous, rather than a granular or particulate, distribution of absorbing material; and in this case the gain in contrast would be equal to the number of passages of the beam of light, the same as if each light ray was following *exactly* the same path at each traverse of the plate.

J. St. Thomas: Has an attempt been made to determine if further contrast gains are possible by means of a series of short intermittent exposures instead of a single long exposure.

M. Cloupeau: No, but it does not seem to me that one could obtain any very great gain in contrast by that method.

Paper E-9: High-Speed Photography Using Ultraviolet Radiation to Eliminate Visible Light Masking in Self-Illuminating Events, *R. Wayne Anderson*, The Dow Chemical Company, Midland, Michigan.

Dr. K.-H. Lohse: Would Mr. Anderson please comment on the following: (a) color temperature of the events, shown in the examples; (b) sensitivity of the films within the ultraviolet spectral region, as compared with the sensitivity within the visible light region; (c) the fact that self-luminous events absorb light in the spectral region in which they emit; (d) whether exposure compensation was employed.

R. W. Anderson: The color temperature of these events would be pretty hard to evaluate. I couldn't give you any definite answer to that part of the question. For the film used, the sensitivity in the ultraviolet region is as much or more than the sensitivity in the visible region. And, there's no exposure correction.

Zev Pressman (Stanford Research Institute, Menlo Park, California): Have you made any comparison between the use of neutral density filters and the results from the ultraviolet-transmitting filter? It seems to be partly a question of avoiding intense overexposure.

R. W. Anderson: I have not had a comparison of these two — it would be very interesting.

Dr. Frank Früngel (Dr.-Ing. Frank Früngel, GmbH. Sulldorfer Landstrasse 400, Hamburg-Rissen(24a), Germany): Our experience with high-pressure argon spark-discharge equipment such as the "Strobokin" equipment shows that, irrespective of the character of the photographic emulsion, the available part of the ultraviolet emission gives an effect which is about 25% of the effect produced by the visible light emitted by the spark. This approximation seems to hold whether the discharge is in argon, krypton, or xenon. There are difficulties in obtaining suitable lens systems for the ultraviolet region, and filters with a steep absorption edge but yet a sufficiently broad transparent passband, for example, in the region between 300 and 350 millimicrons. There is some discussion of this question in the papers we presented at the High-Speed Photography Congresses in 1954, 1956 and 1958.

Paper E-10: The Use of High-Speed Photography and Photoelastic Coatings for the Determination of Dynamic Strains, *C. A. Cole, Jr., and John F. Quinlan*, U.S. Naval Medical Field Research Laboratory, Marine Corps Base, Camp Lejeune, North Carolina; *and Felix Zandman*, Instrument Division, The Budd Company, Phoenixville, Pennsylvania.

Dr. K.-H. Lohse: Can the plastic coatings be used on hot metals? Do the plastic coatings lose their optical effect when heated?

Maj. C. A. Cole, Jr.: In our work, we did not exceed about 150 F on the plate surface, as an estimate. Now when you heat this material, the sensitivity goes down. As long as you know to what level you heated it, you can allow for the effect during the subsequent analysis.

Kaye Weedon (J. L. Nerlien A/S, Nedre Slottsgate 13, Oslo, Norway): Could I ask the name and availability of the plastic coating material?

Maj. C. A. Cole, Jr.: The name of the material that we used is "Photostress." It is put out by the Instruments Division of the Budd Company, Box 345, Phoenixville, Pennsylvania. It is readily available.

Written Discussion

R. O'Regan (Bell Telephone Laboratories, Inc., Murray Hill, New Jersey): The use of a birefringent coating to determine the state of strain on the surface of a metal has been studied by Lee, Mylonas and Duffy.* In an experiment, somewhat similar to the one described in this paper, a metal plate covered with a birefringent coating is struck by a bullet and the residual surface strains are determined. It is shown that the observed fringe order depends not only on the surface strains but also on the curvature that the surface undergoes and the variation of strain across the thickness of the coating. The effect of curvature on birefringence is determined, and it is shown that the error in ignoring this effect can be higher than a factor of two.

The thickness of the coating in the experiment performed at Brown University was 0.125 in., or approximately four times that in the present paper. One would suspect that the error would be substantially reduced by using the thinner coating, but it can still be considerable. Also, the error depends on the curvature of the surface, which can be larger in the dynamic case.

Because the effects of curvature and strain are not separable for the dynamic case and because the effect of curvature cannot be said to be small, I fail to see how quantitative measurements of surface strain can be made by this method.

J. Duffy (Brown University, Providence 12, Rhode Island): This paper contains some interesting applications of birefringent coatings, including a number of good photographs. However, when the authors come to the problem of wave propagation in a rectangular bar, they oversimplify the analysis. For instance, in Figs. 13(c) and 14 the authors make no mention of the fact that there are actually two sets of waves which progress in a strip or a coating cemented to a bar. One wave is the shear wave which the authors obtained and have shown in these figures. But there is a second and more rapid wave which makes a greater angle with the bar. Both of these waves can be seen very distinctly in Fig. 5 of Technical Report No. 2, entitled *The Measurement of Surface Strain by Means of Bonded Birefringent Strips: A Preliminary Report*, by J. Duffy and T. C. Lee, Division of Applied Mathematics, Brown University, Providence, Rhode Island. This report was issued in June, 1959. The reason the photographs in Fig. 14 of the present article do not show both sets of waves is probably that the authors made their strips too narrow. Be that as it may, the authors should be aware that the effects of this second wave in the analysis cannot be neglected. On looking through a slice, say 0.020 in. thick as suggested in Figure 13(c), one will observe the superposed effects of the two waves.

Sigmund J. Jacobs (U.S. Naval Ordnance Laboratory, Silver Spring, Maryland): (1) This commentator is admittedly unfamiliar with the state of the art of dynamic strain observations by use of birefringence methods. He is familiar with the experience of workers engaged in explosive or projectile impact loading of metals and plastics near the region of impact. It has shown us that to a great extent the pressures developed are so high that one can analyze the resultant wave and surface motion as a hydrodynamic phenomenon.† There is definite need for theoretical and experimental tools for dynamically studying solid materials in the region where they do not behave as fluids.

Our experience in dealing with shock loading of fluids has been that when oblique waves are present more often than not the pressure behind such waves is not constant and in addition, rarefaction waves are generally present due to surface unloading. In the present paper thin plastic films are used and it would seem that problems of nonuniform stress or strain must similarly develop.

The following comments and questions are therefore offered with the hope that they will assist us in establishing to what extent the photoelastic methods can be applied in the regions of stress bordering on that in which fluid-like character appears capable of explaining observations. The authors have employed explosives as a means of loading and consequently may be operating in this borderline region.

(2) Apparently the photoelastic method for static strain observation is limited to strains below the elastic limit in the transparent solid. This limitation would seem to apply equally to the transparent coatings. This could mean that plastic deformation could be studied within limits in a coated solid, the limit being the point of plastic deformation in the coating. In applying the photoelastic method to dynamic observations, there appears to be a number of other problems. As a wave passes into the coating, the strain in it is not a constant along a line of sight. The following questions, therefore, arise:

(a) How is the strain pattern related to strain near the wave front?

(b) What strain, if any, can be unambiguously determined? Is it a surface elongation? If so, what experimental evidence is there to prove the point? What is there in the theory of the photoelastic effect which can give confidence in the interpretation of observations?

(3) The entire interpretation of the dynamic experiments seems complex. What seems to be needed is direct correlation of a dynamic photoelastic experiment with another method of observation or with theory for a particular model, one which is preferably so simple that there would be little doubt as to the accuracy of the interpretation. The authors casually relate the polarized light pattern to a shear strain in the model. It is not clear how these shears are formed or transmitted to the coating.

(4) A question arises as to the effect of loading on the polarizing material which in many cases is taped to the model and, therefore, could be locally affected by the motion of the model.

(5) At the 4th Congress on High-Speed Photography at Cologne, there were three papers on photoelastic observations under dynamic loading. There were questions from the floor concerning interpretation. The dynamic problem is certainly not too well understood for elastic-plastic deformation. One should therefore be cautious in trying to predict how far one can go in applying the photoelastic methods to the interpretation of dynamic strain. The paper shows that an effect can be and has been obtained. With further study, it may be possible to use the observation for quantitative measurements.

(6) The abstract indicates that photoelasticity has been widely used in the study of dynamic strains. Can the authors cite a few references both as to the use and analysis by classical photoelastic methods? Has there been prior use of photoelastic methods in dynamic experiments in which transient waves are present?

Authors' Replies to Written Discussion

General

The objective of the paper is clearly set forth in the introduction. We felt that those readers desiring additional information on details and recent developments in photoelasticity and photoelastic coatings should seek this information from publications in those fields.

As an indication of the present status of the method, it can be stated that over 700 companies are using this method for stress analysis of their parts. Among recent applications to well-known structures, one may mention the Atlas missile (Convair

* T. C. Lee, C. Mylonas and J. Duffy, Thickness Effects in Birefringent Coatings with Radial Symmetry, Division of Applied Mathematics, Brown University, Apr. 1959, Technical Report No. 1.

† For bibliography see, S. J. Jacobs, "Recent advances in condensed media detonations," *ARS Jour.*, 30, 4: 151–158, Feb. 1960.

Astronautics), Saturn missile (N.A.S.A. Huntsville, Alabama), 720, 707 and DC8 jets, B58 bomber, 1961 Rambler engine, second-level construction for the George Washington Bridge, Mercury Program for solid rocket propellants, the ligament problem of the Pressure Vessel Research Committee, U.S.S. Skipjack nuclear submarine. Hundreds of other applications are in progress.

Specific Replies

Reply to R. O'Regan

As Mr. O'Regan points out, the thickness of the coating used at Brown University was 0.125 in., or approximately six times larger than necessary for adequate analysis in the elastoplastic range of deformation. The choice by Lee, Mylonas and Duffy of an exaggerated coating thickness was probably dictated by the purpose of the test, i.e., demonstration of correction factors. Their paper shows that the correction factors F and G are extremely sensitive to coating thickness. Using the calculation developed at Brown University in earlier publications and repeated in the cited paper, it is possible to determine the correction factors for the 0.020-in. coating thickness as well as for their 0.125-in. thick coating. Accordingly, the 0.125-in. thick coating yields an error of approximately 50% ($F = 55.9$ and $G = 15.4$), while the 0.020-in. coatings used by us yield an error of approximately 3% ($F = 97.7$ and $G = 0.8$). It is our opinion that an error of such a magnitude (3%) does not preclude quantitative analysis.

Reply to J. Duffy

The experiments of J. Duffy and T. C. Lee employing birefringent strips are directly analogous to those reported here. While Duffy and Lee used a 3-in. wide strip, as compared to the 0.5-in. strip employed in our work, there are no differences in the results that can be ascribed to this detail since the patterns are essentially the same for the first half-inch zone in both cases.

For the determination of surface strains by the photoelastic coating method the investigator must question what coating thickness yields adequate results. Since the birefringent strip shows the actual interface or surface strain condition, it permits estimation of appropriate coating thickness. The integrated birefringence for a thin coating, e.g., 0.020-in., remains an excellent approximation to the surface strain condition as shown in Figure 13(c). For example, in Figure 14(b) at the $6\frac{3}{4}$-in. mark where the interface fringe order is maximum, the fringe order at the interface and the 0.020-in. level are 3.50 and 3.35 respectively; therefore, the average fringe order as obtained in an integration through the 0.020-in. coating thickness is 3.43, leading to an error in the prediction of surface strain of 2%.

In normal application of the photoelastic coating method the investigator desires knowledge of the total surface strain developed in the member, not the individual contribution of longitudinal waves, shear waves, reflected waves, etc. Accordingly, the presence of individual wave contributions was not neglected, but instead, the total strain conditions were considered.

Reply to S. J. Jacobs

(1) In essence the photoelastic coating method can be applied for the analysis of surface strains on any solid body. Special problems may lead to special considerations of experimental technique and furthermore, special considerations regarding the influence of coating thickness as treated in the paper.

(2) The interpretation of photoelastic coating measurements involves some considerations different from those in ordinary photoelastic models. Since strains in the underlying part are to be determined, the major requirement necessary to obtain quantitative data is to have a single valued and predictable relationship between birefringence and strain. Photoelastic coatings which have been used in this test have a linear relationship between strain and birefringence practically to the rupture point of the coating. In essence, a linear relationship between stress and strain in the coating is not required.

(a) This is answered by Figs. 13 and 14 in the text. It is there shown that if the coating is thin enough, the photoelastic pattern will indicate directly the magnitude of the difference of principal strains at any point of the surface, including the front of the wave. For thick coatings, the pattern reveals the integrated value of principal strain differences through the coating thickness.

(b) Photoelasticity is a well-known science. Photoelastic fringes in models or surface coatings yield the integral of the difference of secondary principal strains lying in planes normal to the direction of incident light. This is proved adequately in the literature of the subject (*Photoelasticity*, by M. M. Frocht, J. Wiley & Sons, Inc., New York, 1948; and D. Post and F. Zandman, "Accuracy of Birefringent Coating Method for Coatings of Arbitrary Thickness," *Experimental Mechanics*, Jan. 1961). Adequate understanding exists today for valuable quantitative analysis of those dynamic problems in which very large strains are developed; e.g. analysis of dynamic strain distributions in the case of large plastic deformations since very thin coatings could be used.

(3-a) Indeed direct correlation between various techniques is desired, but the literature of dynamic stress analysis contains extremely meager correlation of this sort. This is evidence of the complexity of the general dynamic problem. At the present time, the investigator is forced to accept rationalization in lieu of absolute proof. It is for this reason that we have studied the interface birefringence with photoelastic strips in addition to direct coating observations. Certainly the future power of dynamic stress analysis methods depends upon careful comparisons and consideration of the results of divers measurements.

(3-b) The relation between the polarized light pattern and shear strain is not casual. It is well known that maximum shear strain acting in any plane in an elastic body is equal to $(\epsilon_1 - \epsilon_2)$, where ϵ_1 and ϵ_2 are the principal strains acting in the same plane.

(4) Polarizers can be loosely taped to the surface of a specimen in such a way that the polarizers are not deformed or loaded together with the specimen.

(5) Regarding dynamic loading of photoelastic models, it is true that the "dynamic problem is certainly not too well understood for elastic-plastic deformation." Indeed, the *static* problem of photoelasticity is not well understood for elastic-plastic deformation. However, this is irrelevant to the problem at hand. In the case of the coating method, a linear or predictable strain versus birefringence relationship is required. The stress-strain relationship for the coating is of little consequence.

(6) Indeed, photoelasticity has been widely used to determine strains in transparent models as evidenced by many publications, including: A. J. Durelli, "Experiments for Determination of Transient Stress and Strain Distributions in Two-Dimensional Problems," *A.S.M.E. Transactions, J. Applied Mechanics, 24, No. 1:* Mar. 1957; Frocht and Flynn, "On Saint Venant's Principle Under Dynamic Conditions," I.I.T. Technical Report No. 8, Jan. 1959; Frocht et al., "Dynamic Photoelasticity by Means of Streak Photography," *S.E.S.A. Proceedings, 14, No. 2:* 1957; Frocht and Betser, "Photoelastic Study of Maximum Tensile Stresses in Simply Supported Short Beams Under Circular Transverse Impact, *A.S.M.E. J. Applied Mechanics, 24, No. 4:* Dec. 1957; Flynn and Frocht, "Studies in Dynamic Photoelasticity," *J. Applied Mechanics, 23:* 1956.

Also, very interesting papers on the same subject have been published by Kolsky, Senior and Wells, Wells and Post, Clark, and others.

Methods for observing and measuring birefringence with polarized light are not new, but have been used throughout the history of photoelasticity (first measurements made about 1820) and may be considered classical.