THE PHOTOGRAPHIC STUDY OF RAPID EVENTS

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PREFACE

THIS monograph is not a text-book. The photographic methods which are used for the study of rapid events are now so diverse that I cannot hope to give more than the general basis of some of the more important experimental methods. I have separated the techniques themselves, and their applications, into two parts of this book, although there is inevitably some overlapping. The expert in any particular aspect of the field will perhaps forgive a broad approach in which some of the argument is necessarily shortened. I hope that the research worker who has not yet used the tools of high-speed photography will see that there are valuable aids to help him with his problems.

The discussion is confined to the photographic recording of actual images of the primary event. No mention is made of methods which record secondary phenomena arising from the primary event. For example, high-speed cathode-ray oscillograph recording of rapid transients is not mentioned, since this is really a subject in itself. The photographic emulsion methods now widely employed for the study of nuclear phenomena have been adequately described elsewhere.

It is a great pleasure to acknowledge the stimulus of many discussions with my colleagues in the Royal Naval Scientific Service during our study together of various problems in this field of photographic research. In particular, R. P. Coghlan and W. R. Stamp devised the methods described in Chapter IV of measuring photographically the growth and decay of light from short duration flash-discharge tubes, R. B. Phillips has worked with me on the problems of design of drum cameras in which the film is stationary, and J. B. Collins and H. J. Hodges have shown the practical possibilities of taking slow-motion films in the ocean itself. A. C. Glandford's endless patience has produced many of the illustrative plates from difficult material.

L. A. Sayce, H. K. Bourne, C. A. Adams, and R. S. Allan were kind enough to make valuable criticisms of the manuscript. R. S. Schultze was good enough to arrange for me to consult various bibliographic material normally inaccessible.

LONDON, *January* 1950 W. D. C.

INTRODUCTION

In many problems in scientific research, events or processes occur in a short duration of time, so that they cannot be observed visually, but must be recorded by photographic means. The precise sequence in the event may then be studied later, either by viewing a slow-motion film projection, or as a series of separate pictures prepared for detailed analysis and measurement.

Particularly during the last quarter of a century, the technical advances made both in cine camera design, high intensity light sources, sensitive emulsions of great speed, wide aperture optical systems and high running-speed mechanisms, have all contributed to the branch of scientific photography now generally termed high-speed photography. In this monograph the term will be used to include both the taking of pictures at high repetition rates, and also the methods in which single short exposure time pictures are taken of certain phases of a phenomenon. The latter methods are often used for non-recurrent events.

In the last decade the urgent pressure of war research has been the primary reason for the new developments in techniques of high-speed photography. The study of weapons which move with high velocities, from the points of view both of their general trajectory, and their detailed behaviour in flight, has led to the production in Service laboratories in the belligerent countries of powerful analytical techniques. Explosion phenomena, both in the air, and underwater, have been examined by these methods. The recording devices here used have a wide application to many sciences—indeed this application has already begun. It is the aim of this book to give some idea of the possibilities and limitations of the methods. It is hoped that a broad survey of this nature will make it clear to research workers that recent advances can assist them in their investigations of fundamental processes. The war-time applications may well be matched by equally dramatic and elegant techniques in the scientific developments of peace-time research.

The range of techniques which is now available is classified in Chapter I. The classification is made according to the picture-repetition rate at which the photographs are taken, since this is one of the most fundamental parameters in the method chosen for solution of a particular problem. As the picture-repetition rate progressively increases, so the total time for which an event can be studied is proportionately reduced. The techniques then grow in complexity, and the problem of synchronizing the photographic recording devices with the event studied, becomes more elaborate.

Chapter II describes the existing methods of photography in the lower ranges of repetition rate, so that the later techniques are understood in a proper historical perspective. The problems at these lower speeds are mainly concerned with camera design and film transport, together with the production of fine optical quality of the system.

In Chapters III and IV two fundamental aspects of the problem are dealt with in some detail. The lighting of the subject under study is of primary importance, since only in the case of self-luminous objects is a simplification of method possible. The use of various light sources for the purpose is described and their characteristics and limitations are discussed. Later the question of choice of sensitive material to be used is studied, for at very short exposure times, the way in which the emulsion reacts to the light it receives is of considerable importance. The response is not only affected by the exposure time values involved, but also by the processing techniques used after exposure. The performance of the emulsion may often be the limiting factor in the technique.

In Chapter V an account is given of some aspects of single-picture techniques which are used often for the study of unique events in processes which are non-recurring. These often involve the pulsing of discharge lamp sources by high-power condenser discharges, at a suitable synchronized time in the history of the event. Methods devised for these studies are highly adaptable for research purposes because of their flexibility.

Chapter VI deals with what will be termed film drum cameras. Here are classified cameras in which the film is not transported through a mechanism, but is attached to a drum. The drum itself may then be turned at a high rotational speed, or the film may be kept stationary and rapidly rotating optical parts may cause the images to be formed successively on the stationary film.

In Chapter VII the diversity of methods of spark and Schlieren photography is reviewed, which makes possible both exposures of less than one microsecond and repetition rates of a million per second of a limited number of pictures. Here specialized optical systems are combined with the photographic procedures.

Chapters VIII, IX, X, and XI give a number of examples from various sciences of the applications of high-speed photography. In zoological studies of the motion of animals, insects, birds, and even fishes in the ocean, slow-motion techniques have already begun to be used. In the biological and medical sciences the applications are not as widespread as in physical and engineering research. It is in military applications that some of the most notable advances have been made.

Thus, two-thirds of this book (Chap. I–VII) deals with the photographic techniques which are used to study rapid events. The other one-third (Chap. VIII–XII) reviews the applications of these methods in various sciences, and suggests ways in which the techniques, and modifications of them, may be further applied in research.

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PART I

THE TECHNIQUES USED

CHAPTER I

CLASSIFICATION OF TECHNIQUES

THE rapid events which are studied in various sciences by photographic methods rarely last for more than one second of time, in which short period it is necessary to record the pattern of the process for subsequent study and analysis. The methods by which these records are made are the subject of this monograph, and some examples will be given of the wide field of research in which they are employed.

A somewhat loose term, 'high-speed photography' has often been used to cover these studies. The methods are the antithesis of the technique known as 'time lapse' photography, where a series of pictures is taken at widely spaced intervals of time, so that the motion as subsequently viewed on the film is apparently speeded up. In this latter case, the time scale is compressed; in the cases under study in this book, the time scale is stretched. Whereas time lapse methods for slow processes have been widely used in medical, zoological, and biological studies, the study of rapid events has so far been mainly in the fields of engineering, physics, and military research.

In the techniques used, a distinction may be drawn between those which produce a series of pictures for subsequent cinematographic projection, and those which do not. In the latter case individual separate pictures permit study of movement by comparison. The former type of picture is generally possible only in the lower orders of picture-taking speed. The latter type permits great flexibility of method and analysis.

1. Rapid Events. Extended or localized movement

A distinction may be made between two types of rapid events, those which move with a high translational velocity (extended movement), and those in which there are rapid inherent changes with time in the process under investigation (localized movement). In both cases the photographic method is used to magnify the time scale of the event, so that processes which cannot be perceived by the eye may be analysed later from the photographic record.

It is worth examining the velocity scales and time scales of some typical events in order to be clear about the orders of speed of some of the processes which are being investigated.

Consider the velocity values of some typical events which vary over a range of speed of about 10^8 to 1, some of which are listed on Table I. At the lower end of the scale, at say 3 m./sec., lie many of the occurrences of everyday life. Translational velocities above this speed very rapidly become too fast for the eye to perceive in detail. At the other end of the scale, a factor of 10^8 higher, is the velocity of light, and, in all the successive decades of speed in between, lie the natural and artificially created velocities of physical experience. At a speed of 30 m./sec. is the express train, and in the same region of velocity is an athlete running, a bird in a rapid dive after prey, and a destroyer at full speed. Another factor of 10 in velocity, and the speed of sound in air is reached. Of the same order are flying bullets which move at rather higher speeds—a stone falling under gravity (neglecting air drag) from the top of Snowdon to sea-level would reach at its terminal velocity about half the speed of sound. The compression waves formed in the violent fracture of plate-glass move at another factor of 10 times this speed. At another decade higher, in the speeds above 10^4 m./sec., is the speed of the earth round the sun, or the movement of the leader stroke of a lightning discharge. Higher still, at speeds of 10^5 m./sec., few man-made events occur. At 3×10^6 m./sec. is reached the orbital velocity of an electron in a hydrogen atom, and at 3×10^7 the velocity of an electron after acceleration through 10,000 volts. Here already are velocities approaching 1/10th that of light. Only events in the lower part of this velocity scale can be photographed directly, and beyond a velocity of 10^4 m./sec. recording difficulties are very great.

TABLE I

The Velocity Scale of Some Events

Event	*Velocity*	
	m./sec.	*mm./microsec.*
	1	10^{-3}
Many normal events	3	0·003
	10	10^{-2}
Athlete running	10	0·010
Destroyer at 30 knots	15	0·015
Bird in power dive	20	0·020
Express train at 70 m.p.h.	30	0·030
	10^{2}	10^{-1}
Stone falling under gravity through 1,100 m. (Height of Snowdon)	$1{\cdot}5\times10^{2}$	0·15
Sound in air	$3{\cdot}3\times10^{2}$	0·33
Flying bullet	$8{\cdot}0\times10^{2}$	0·80
	10^{3}	1
High velocity projectiles	$1{\cdot}0\times10^{3}$	1·0
Sound in water	$1{\cdot}5\times10^{3}$	1·5
Compression waves in fracturing glass	$5{\cdot}0\times10^{3}$	5·0
Flame propagation in explosion	$8{\cdot}0\times10^{3}$	8·0
	10^{4}	10
Leader stroke of lightning discharge	$1{\cdot}0\times10^{4}$	10
Expansion rate of fuse wire on violent overload	$1{\cdot}5\times10^{4}$	15
Speed of earth round the sun	$3{\cdot}0\times10^{4}$	30
Meteor velocities in space	$4{\cdot}0\times10^{4}$	40
	10^{5}	10^{2}
	3×10^{5}	3×10^{2}
	10^{6}	10^{3}
Orbital velocity of electron in hydrogen atom.	3×10^{6}	3×10^{3}
	10^{7}	10^{4}
Main stroke of lightning discharge	1×10^{7}	1×10^{4}
Electron after acceleration through 10,000 volts	3×10^{7}	3×10^{4}
	10^{8}	10^{5}
Light	3×10^{8}	3×10^{5}

There is a similar wide range in the time scale of studied rapid events of the order of 10^7 to 1, from 10 seconds to 1 microsecond.

Some typical examples of the time of various processes are listed in Table II, where it will be seen that the events quoted do not move with a high translational speed, but their occurrence lasts only a short time. These are localized movement events.

Events in this wide range of time are studied photographically. In those labelled A to F in Table II, cine film records have been made. The objects of the research on these processes and the experimental techniques used, are most diverse, and the results of the investigations have enabled notable advances in understanding to be made. Many of the methods have the great advantage that they do not disturb the phenomenon itself.

TABLE II

The Time Scale of Some Events

Event	*Time*	*Reference*
Complete history of major blasting operation .	100 sec.	A
Formation of a spray plume from underwater explosion	10 ,,	B
Incandescence time of Tungsten lamp having wire 0·012 in. diam.	1 ,,	C
Typical time for wing beat of insect . .	100 millisec.	D
Single rotation of car flywheel performing 6,000 r.p.m.	10 ,,	E
Operation of fast focal plane camera shutter .	1 ,,	F
Total time of charge detonation . . .	100 microsec.	G
Duration of light from Xenon flash tube discharge	10 ,,	H
Duration of air spark	1 ,,	J

2. Fundamental Factors

It will be appreciated that in order to study a range of event velocities and time scales of this order, a considerable range of magnification scales in time is demanded in the record. Now a fast event may be studied by two different methods—according to its inherent nature. If it is a process which is unique and non-recurring and cannot easily be repeated experimentally with precise time accuracy, then it must generally be studied by a series of successive photographs at a high repetition rate. If it is an event which can be reproduced accurately on successive occasions, then a series of very short exposure single pictures taken in successive experiments at different times from a zero point may suffice for the study.

2.1. *Picture-repetiton rate* (*R*)

Methods of recording a rapid succession of pictures may be conveniently classified according to the repetition rate of taking and consequently the time magnification they give to the event studied. Suppose that an ordinary cine film, in which 24 pictures are recorded every second, is taken of an event which lasts 100 seconds. If it is then projected at the picture speed at which it was taken, the time magnification of the events seen will be unity, and there will be 2,400 separate pictures made of the various phases in the occurrence on the 160 feet of film record. If now, the event is completed more rapidly and lasts for only 10 seconds, and again a series of 2,400 pictures is required, the repetition rate of the pictures has to be 10 times higher and the projected film (at 24 pictures per second) will give a time magnification of 10 times that of the original cine film. Corresponding increments of 10 times in repetition rate give equivalent changes in time magnification (see Table III).

TABLE III

Time Magnification Scales

Ref.	*Total duration time of event. Secs.*	*Total no. of pictures required of event*	*Necessary picture-repetition rate*	*Time magnification projected at 24 pictures per sec.*
A	10^2	2,400	24	1
B	10	,,	240	10
C	1	,,	2,400	10^2
D	10^{-1}	,,	24,000	10^3
E	10^{-2}	,,	240,000	10^4
F	10^{-3}	,,	2,400,000	10^5

Each of these successive multiplications of picture-repetition rate by a factor of 10, leads to greater complication in method, and it is these complications which have led to many interesting developments in the optical design of cameras, and in various recently constructed discharge lamp devices. In the methods where a series of photographs of an event are taken in rapid