

THE REPRODUCTION AND MEASUREMENT OF VERY SHORT
INTERVALS OF TIME.

BY JOHN COULSON.

IT is often found desirable to have at one's disposal some means by which two neighboring electric circuits can be broken in quick succession in such a way that the interval between these two operations is accurately predictable and under the control of the experimenter. This paper contains a brief description of a simple apparatus which can be made to give time intervals of very short duration.

This work was suggested to the writer by Professor B. O. Peirce, to whom it was of much interest, since he required in his investigation of the dielectric constants of certain materials, a shorter time interval than was attainable, with accuracy, by any known apparatus. The many devices then in use either gave intervals much longer than would serve, or intervals which could not be repeated with a sufficient degree of accuracy.

The measurement of very short intervals of time is a matter of but little difficulty. More than sixty years ago Helmholtz¹ used in his investigation "*Sur la vitesse de propagation de l'agent nerveux dans les nerfs rachidiens*," a horizontal magnetic pendulum for determining the duration of an electric impulse. The apparatus was of the form of a Thompson galvanometer, and the angular deviation of the magnet from its position of rest was taken as a measure of the duration of the electric impulse sent through the galvanometer. The behavior of such swinging magnets had been studied by Gauss and W. Weber² while making their magnetic measurements at Göttingen.

Of the many methods used by later investigators for measuring such intervals, perhaps the best is by determining either the partial discharge from a loaded condenser,³ when short-circuited during the interval in question through a given non-inductive resistance, or the fractional part

¹ Helmholtz, *Comptes Rendus*, 30, 1850; 33, 1851.

² Gauss, and W. Weber, *Resultate des Magnetischen Vereins*, 1837.

³ H. R. Kempe, *Handbook of Electrical Testing*, 1887, 4th ed.; Mascart and Joubert, *Electricity and Magnetism*, 1888, Vol. 2; Devaux-Charbonnel, *Comptes Rendus*, 142, 1906; *L'Electricien*, 31, 1906; H. W. Morse, and C. L. B. Shuddemagen, *Proc. Am. Acad.*, 44, 1908; C. L. B. Shuddemagen, *Proc. Am. Acad.*, 44, 1908.

of a full charge acquired by an originally empty condenser through a given non-inductive resistance when a constant-electromotive force was applied throughout the charging time interval. It has long been known that by a proper choice of apparatus this method of procedure yields very accurate measurements, and is capable of being applied in a variety of ways. It furnishes a satisfactory means of determining the time of contact of a hammer and an anvil,¹ or the velocity of a projectile, or the "specific duration"² of impinging spheres. For many years Professor Peirce had as regular experiments in his course on experimental electricity and magnetism, the determination of cable insulation resistance, and the time of contact of two impinging steel balls, as applications of this method. He also applied it in his investigation on the duration of a "quick tap on a telegraph key."³ In every case, when the apparatus was properly set up, this method has proven to be a good one, yielding results which are limited in accuracy only by the unsteadiness of the ballistic galvanometer used to measure the condenser charge.

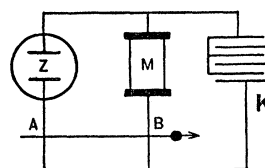


Fig. 1.

Apparatus arranged for the determination of the unloading time.

The problem of finding the fractional part of a full charge left on a condenser after unloading through a non-inductive resistance for an interval of t seconds is a simple one, and the solution is very familiar. Let the apparatus be arranged in some such form as indicated in Fig. 1, where Z is a battery of constant-electromotive force, M a variable non-inductive resistance, and K a standard condenser. Suppose the condenser has acquired its full load Q_0 ; then, if the battery lead be severed at A by a rifle ball, the condenser will discharge through the resistance r , made up of M and the lead wires, until the ball cuts the second wire at B ; and the charge left on the condenser will be, $Q_t = Q_0 e^{-t/kr}$ where t is the time taken by the bullet to travel from A to B , and k the capacity of the condenser in farads. If t is the quantity sought, as in the present investigation,

$$t = kr \log_e \frac{Q_0}{Q_t}.$$

With the aid of a suitable ballistic galvanometer and key, both Q_0 and Q_t can be easily determined.

The design of an apparatus which will repeatedly give the same ex-

¹ R. Sabine, *Telegraphic Journal*, 4, 1876; *Phil. Mag.*, 1, 1876.

² A. E. Kennelly, and E. F. Northrup, *Journal of the Franklin Institute*, 1911.

³ B. O. Pierce, *Proc. Am. Acad.*, 42, 1908.

tremely short interval of time within say one per cent. of itself, so that it can be controlled and used without measuring its duration in every experiment, is a matter of much greater difficulty. It has been customary

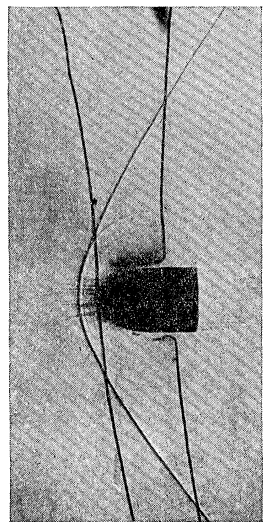


Fig. 2.

Bullet, travelling with a velocity of 500 meters per second, in the act of breaking two parallel wires placed in its path. It is evident that the ruptured wire bent very perceptibly before breaking.

to use a bullet travelling at a high velocity to sever two parallel lines placed close together, but the results from successive observations by this method often differ as much as 25 per cent. Fig. 2 is reproduced from the photograph of a bullet which was in the act of severing two wires while travelling at a velocity of 500 meters per second. The photograph was taken by Mr. W. A. Hyde, Bureau of Ordnance, Navy Department, to whom I am indebted for permitting its reproduction. It illustrates what has long been known, that even the most brittle material, placed in the path of a bullet under high velocity, will bend before it breaks, and very often drag on the sides of the bullet; which in either case may cause serious errors.

The apparatus here described is based on a different principle. If a massive weight, falling freely under gravity, strikes a collar on a metal rod which is supported vertically, an elastic wave or impulse travels out along the rod in each direction from the collar with a finite velocity.¹ It is evident that if the impact takes place at the middle point of the rod, these waves will reach the ends of the rod at the same time. If, however, the point at which the impact occurs be not at the middle of the rod, the impulses thus started will reach the ends at times that differ by an interval which will depend on the path differences. In this way controllable time intervals extending over a considerable range may be secured, and can be measured easily with the aid of proper apparatus. I have experimented with numerous forms in order to be sure that the elastic wave excited in the comparatively long stout metal rods used was of sufficient magnitude to interrupt the passage of current in two related circuits, of which the rod in question formed a part, by breaking contacts at its extremities.

Fig. 3 shows diagrammatically the arrangement of the apparatus which has given the most consistent results. The framework, about 2 meters

¹ A. E. H. Love, *Mathematical Theory of Elasticity*, 2d ed., 1906.

in height, and 40 centimeters wide, constructed from well seasoned pine studs 5 centimeters thick, and 15 centimeters wide, stands on a concrete foundation, and is bolted to the brick wall of the laboratory thus avoiding all possible jarring of the apparatus when in use. The central crosspiece, which is subjected to heavy blows when the apparatus is in operation, consists of a heavy block of oak set into the sides of the frame, and held fast by long screws. The rod *AB*, which serves as a circuit breaker is of Bessemer steel 1.3 centimeters in diameter, it terminates in a square metal block

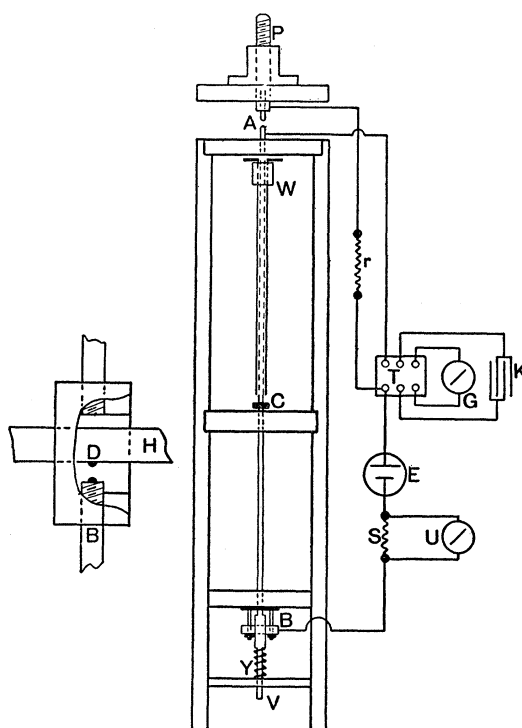


Fig. 3.

Diagrammatic arrangement of the apparatus used in making the observations described in this paper.

pierced by a rectangular hole, and is held vertical by passing through holes in the center of the cross pieces. It is supported in the position of closed circuit by a spiral steel spring *Y*, the lower terminal *B* resting against the fixed contact *D*, in the cast iron bar *H* which passes through the rectangular hole in the square block attached to the end of the rod, while the upper terminal *A* comes in contact with a piston which is inserted in the screw *P*. The cast iron bar is well insulated on both sides by strips of hard rubber, and is supported by stout pillars on a metal

base which is attached rigidly to the frame. The pressure of the piston at the upper terminal of the rod is regulated by a weak spiral spring inserted in piston hole. To avoid the violent jar which results from the sudden stopping of the weight, this part of the apparatus is fixed on a separate shelf attached to the wall. The weight W , which is about 12 kilograms, slides on a brass tube supported independently by a bracket, thus protecting the rod from the downward motion of the weight until it has reached the collar C , the desired point of impact. The collar, or anvil consists of a thick disc of self-hardening steel, fastened rigidly to the rod by a steel set pin and silver solder, and is the fixed origin of the elastic waves set up in the rod by the sudden shock. The impact carries the rod down until the collar reaches the heavy wooden cross piece below. It is held from rebounding by means of a spring latch. The elastic waves on which the operation of the apparatus depends are propagated from C to A and B respectively.

The arrangement of the electrical apparatus is very simple, as will be seen from the diagram, but great care was taken to have all parts highly insulated. The connecting wires are all enclosed separately in small rubber tubing, and then placed side by side in order to avoid self inductance. The battery E consists of three bichromate cells in series, placed on a platform supported by glass insulators. A sensitive galvanometer U , shunted by a low resistance S , served as a check on the constancy of the current in the circuit. The double pole double throw switch T , consisted of hard rubber with platinum contacts, and is operated by means of a long brass rod attached to the armature of a strong electro-magnet placed at some distance from the apparatus. A bank of storage cells supplied the current to work the electro-magnet, which by suitable keys and an automatic interrupter driven by a time clock, could be made to throw the switch T in either one direction, or the other at a given instant. In this way the poles of the condenser K , which is a standard microfarad condenser (Elliot Bros., No. 72) recently calibrated at the Bureau of Standards, was brought into the position of loading, or the reverse; that is across the terminals of the standard non-inductive resistance r , or in series with the galvanometer G , which is a ballistic d'Arsonval of high sensibility.

In taking the observations the manipulation of the apparatus, from the instant the condenser began to load, was entirely automatic; thus eliminating errors from variation in charging time, and otherwise.

The method of procedure was as follows: With the rod in closed circuit, and the weight W in its elevated position, the condenser was thrown into circuit with r at the signal from the time clock, which later, after a

predetermined interval, released the weight. The elastic wave travelling downward then broke the contact *B*, leaving the condenser to discharge through *r* until the wave travelling upwards reached the second contact at *A*; and before either end of the rod had time to regain its closed position the impact carried the rod bodily downward into the position of open circuit. On reaching this position it closed a key at *V*, which operated the electromagnet, which in turn discharged the condenser through the galvanometer immediately. In this way, using different values for *k* and *r*, many sets of observations were taken in quick succession. The results from three different rods, divided in different ratios by the steel collar, are tabulated below, Table I.

TABLE I.

Rod.	<i>r</i> in Ohms.	<i>k</i> in Microfarads.	Log _e <i>Q</i> ₀ / <i>Q</i> _t .	<i>t</i> × 10 ⁶ Seconds.
<i>L</i>	800	0.05106	0.3818	15.61
<i>L</i>	700	0.05106	0.4383	15.69
<i>L</i>	600	0.05106	0.5038	15.45
<i>L</i>	500	0.05106	0.6206	15.82
<i>L</i>	400	0.05106	0.7701	15.75
<i>M</i>	600	0.05101	0.0988	3.028
<i>M</i>	400	0.05101	0.1484	3.030
<i>M</i>	200	0.05101	0.2964	3.025
<i>N</i>	800	0.05101	0.1570	6.41
<i>N</i>	700	0.05101	0.1814	6.50
<i>N</i>	600	0.05101	0.2110	6.48
<i>N</i>	500	0.05101	0.2502	6.40
<i>N</i>	401	0.05101	0.3148	6.44
<i>N</i>	201	0.10228	0.3118	6.41

The apparatus described here is the result of many efforts to construct one that would function consistently for a given rod. The contacts at *A* and *B* were sources of much trouble; platinum, silver, hard steel, German silver, and platinum-iridium terminals were experimented with. The platinum and silver contacts were too soft; the German silver and steel offered contact resistance when used for any length of time, but the platinum-iridium terminals proved to be entirely free from these defects. In the early experiments the inductance in the battery circuit was also a source of disturbance, but this was alleviated by carrying the lead wire from *B* parallel to the rod, and close to it, through a hole in the collar, and out at *A*, where the well insulated wires all came together. The consistency with which the apparatus worked finally, is illustrated by a set of observations taken with rod *L*, Table II.

It will be seen from Table I. that the greatest deviation in time interval, which elapses between the interruption of the currents, in a given rod, at

TABLE II.

$r = 800$ Ohms.		$k = 0.05106$ M. F.	
Galvanometer Deflections, αQ_t .	Galvanometer Deflections, αQ_0 .	$\log_e Q_0/Q_t$.	$t \times 10^6$ Seconds.
8.18 cms.	11.98 cms.	0.3818	15.61
8.20	12.05		
8.30	12.20		
8.31	12.12		
8.25	12.09		
8.30	12.10		

the points B and A when different combinations of resistance and capacity are used, is about 2.5 per cent., as compared with the 25 per cent. obtainable with a bullet. In Table II., which is a typical set of observations, the agreement is about 1.2 per cent. If the resistance and capacity be well chosen, for a given rod, a set of observations should not differ from each other by more than 1 per cent.

I wish to express my indebtedness to the late Professor B. O. Peirce for his many helpful suggestions throughout the work, and for the loan of the standard apparatus used in making the observations mentioned in this paper.

THE JEFFERSON PHYSICAL LABORATORY,
CAMBRIDGE, MASS.,
April, 1914.

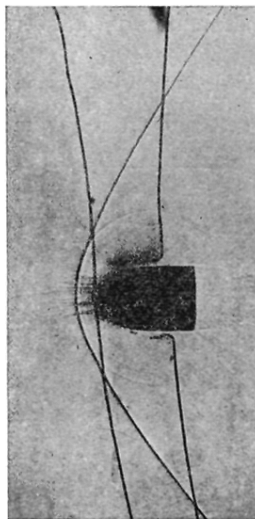


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Bullet, travelling with a velocity of 500 meters per second, in the act of breaking two parallel wires placed in its path. It is evident that the ruptured wire bent very perceptibly before breaking.