EXPERIMENTAL TECHNIQUES IN BALLISTICS—I

DETERMINATION OF MUZZLE VELOCITIES

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ABSTRACT

An account is given of the more common experimental methods used in ballistics for the determination of the muzzle velocities of projectiles.

Introduction

Accurate experimental determinations of the various quantities of interest in ballistics (like the muzzle velocities of projectiles, the maximum pressure attained in the gun, the pressure-time curve, the time of flight, the spin, the yaw etc.) are very necessary for a variety of reasons —for checking existing theories, for developing more refined theories and for the practical testing of the performance of weapons. But the quantities to be measured are so extraordinarily outside the normal range that quite a lot of ingenuity has had to be devoted to the development of suitable experimental techniques. Thus velocities of projectiles almost always in the supersonic range, pressures of the order of 20 tons per square inch acting for a few milliseconds, time intervals of the order of a hundredth of a second—all these have to be measured to a high degree of accuracy.

In the determination of muzzle velocities, it may be noted that we do not measure the velocity of the projectile when it just leaves the muzzle. The projectile continues to be accelerated for a short distance even after the muzzle by the powder gases. Secondly, the effect of the muzzle blast damages the measuring apparatus if it is too close and we are forced to keep the apparatus a safe distance from the gun. Thirdly, we do not actually measure the velocity of the projectile at a particular point (except with the ballistic pendulum which, however, is not accurate). We measure the time taken by the projectile to travel a definite distance (the base) and we assume that the observed velocity got by dividing the distance by the time corresponds to the velocity of the projectile when it is midway along this distance. This assumption is normally justifiable. Normally, we must be able to measure correct to 0·1% even though a higher degree of accuracy may be required when we wish to study the retardation of the projectile in flight or the round-to-round variation of muzzle velocity. From a knowledge of the velocity of the projectile at a definite distance from the muzzle, we may deduce the muzzle velocity by applying external ballistic laws. Usually, the velocities at two known distances from the muzzle are determined and the muzzle velocity deduced by using Siacci's equation.

(*a*) *The Ballistic Pendulum*

This ballistic pendulum was used for the determination of projectile velocities in the eighteenth century by Benjamin Robins who was able to deduce valuable information on air resistance to projectile motion. As the method is not very accurate and is now seldom used, it will not be described here.

(b) *The Boulenge chronograph*

This instrument, invented by Boulengé of the Belgian army in 1874 is even now being extensively used for the determination of muzzle velocities. Here the time taken by the projectile to travel a definite known distance is determined indirectly in terms of the distance through which a body falling freely under gravity moves in that time interval. Two wire screens which form part of two independent circuits are set up at a known distance apart in the trajectory. The passage of the projectile through the first screens breaks the first circuit and a rod held suspended by the attraction of an electromagnet starts falling. Similarly, when the second screen is broken, a second rod starts falling. After falling a certain distance, this rod strikes a trigger which releases a knife (held back by a spring) which then cuts a mark on the first rod which is still falling freely. The position of this mark depends on the distance through which the first rod has fallen in a time equal to the time interval to be measured plus the time for the second rod to fall and the knife to cut its mark. This latter time is determined and suitably accounted for.

The screens—Each screen consists of a wooden framework with insulated pegs at its ends. A continuous strand of fine wire is stretched back and forth between the pegs. The separation between adjacent turns of wire is less than the calibre of the gun. The screens are generally spaced at intervals of 120′, 180′ or 270′. The separation is chosen such that the time taken by the projectile to travel this distance is about 0·1 second. The minimum distance between the near screen and the muzzle may vary from 50′ to 300′ (depending on the calibre of the gun). When firing at elevation, the screen is mounted on a trolley, raised on to the trajectory and suitably suspended, precautions being taken against the displacement of the screens by wind. When two or more screens (operating separate chronographs) are used simultaneously, the interval between successive independent screens is chosen sufficiently large (at least greater than length of projectile) to ensure that there is no interference between the independent circuits. When firing small arms projectiles, the near screen may be replaced by a single fine wire (which may be at a distance of 3′ from muzzle) and the far screen by a contact screen consisting of a metal plate supporting on its rear face a spring contact. When the projectile strikes the plate, the electrical circuit which is completed through the spring contact is broken.

The chronograph—The chronograph is mounted on a pedestal which is a solid concrete pillar sunk well into the ground. It is ensured that there is no possibility of any local disturbance affecting the instrument. The chronograph should be sufficiently far away from the gun so that the amplitude of the ground wave caused by the firing (the ground wave velocity may exceed the projectile velocity) becomes inappreciable at the site of the instrument.

The instrument (Fig. 1) consists of a vertical brass pillar supporting on either side an electromagnet. One magnet is rigidly fixed to the top of the pillar and supports a rod about 22″ long. The other magnet can be varied in height and supports a rod about 5″ long. The magnets have separate circuits, the upper magnet being connected to the near screen (nearer muzzle) and the lower one to the far screen. When the projectile pierces the first screen, the circuit of the first magnet is broken and the long rod starts falling. There is provision for its uninterrupted fall into a deep recess in the instrument base. When the second screen is pierced, the short rod starts falling, and after falling about 4″ strikes a trigger which releases the knife which makes a mark on the still falling long rod.

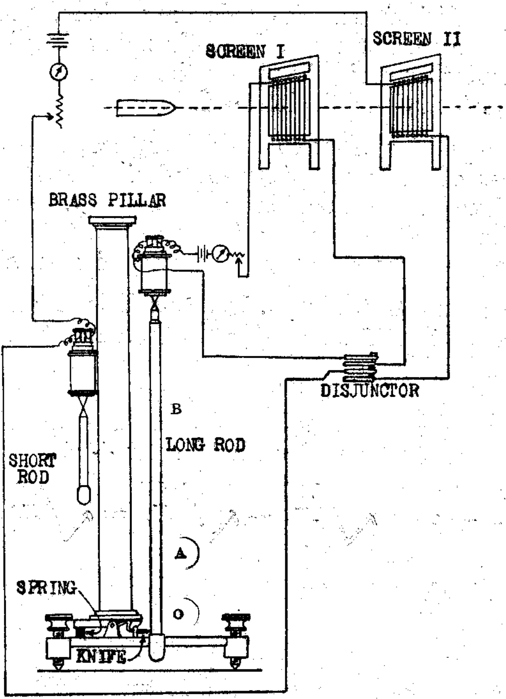


FIG. 1—Boulenge chronograph.

Each rod (of weight $10\frac{1}{2}$ oz.) consists of a phosphor bronze tube having at the upper end a soft iron pole piece and at the lower end a rectangular metal bob (to keep the centre of gravity low). To avoid damage, the long rod is surrounded by a renewable copper sheath on which are made the knife cuts. By suitable design of the soft iron pole piece, the long rod is magnetically prevented from rotating. The points of the magnets are of standard form and are kept bright and free from irregularities. The current through each magnet is so adjusted that it just fails to support the rod when a weight of 450 grains is added to it. The current is of the order of 0·1 ampere and the circuit is fed from 12V batteries. It is ensured that when released, the knife edge travels horizontally on striking the rod.

An initial mark (zero mark) is made by releasing the knife by hand while the long rod is still hanging. If now the two rods are released simultaneously, a cut will be made about 4″ above the zero mark. The distance between this and the zero mark is that travelled by the long rod when the short rod falls and operates the knife. This time interval (disjunction time) may be adjusted by raising or lowering the short rod magnet. The disjunction time has been chosen to be 0·15 second corresponding to a free fall of 4·345″. The instrument is first adjusted before use so that the disjunction time is exactly 0·15 second. For this, a line (disjunction line) is marked on the long rod at 4·345″ above the zero mark. The short rod magnet is raised or lowered until the cut made by the knife when both rods are released simultaneously is exactly on this line. To break both circuits simultaneously, a special arrangement (the disjunctor) is used. After checking the disjunction, the rods are again hung from the magnets. The instrument is now ready for use. When the near screen is broken the first rod starts falling and when projectile pierces the seconds screen later, the short rod falls and a mark is made on the long rod.

For reading the position of the cut on the long rod, there are special scales. In the modern types of scales, the midscreen velocity can be read directly and readings can be taken for a pair of rods simultaneously. There is provision for direct reading of the velocity for screen distances of 120′, 180′ and 270′. It is a simple matter to get the velocity for any other screen distance also, if necessary.

Let O be the zero mark, (Refer fig. 1), A the disjunction mark and B the velocity mark. If τ_1 be the time taken by the short rod to fall and strike the trigger and τ_2 the time taken for the knife mechanism to function, $\tau = \tau_1 + \tau_2$ is the disjunction time (which is adjusted to be 0·15 seconds.) Let $OA=h_o$ and $OB=h_1$. $\therefore\ h_o = \frac{1}{2}g\tau^2 = 4\cdot345''$. If t be the time taken by the projectile to pass between the two screens, we have $h_1 = \frac{1}{2}g\,(t+\tau)^2$.

$$\text{or}\quad t = \sqrt{\frac{2h_1}{g}} - \tau = \sqrt{\frac{2h_1}{g}} - \sqrt{\frac{2h_0}{g}} = \sqrt{\frac{2h_1}{g}} - 0\cdot15.$$

Thus t can be found. If s be the distance between screens, the velocity $v = \frac{s}{t}$

The accuracy of the chronograph

It is important to note that the special feature of the Boulenge chronograph, *viz.* disjunction, serves to increase the accuracy of the instrument, as can be seen from the following considerations.

If h be the height fallen by the rod in time t and u its velocity at time t, we have

$$h = \tfrac{1}{2}\,gt^2 \text{ and } u = gt.$$
$$\therefore\ \Delta h = gt\,\Delta t = u\,\Delta t.$$

Thus for a given error Δh in measuring the height of fall, the error in time Δt is inversely proportional to the velocity of the rod when it is struck by the knife. The velocity being proportional to the time of fall, a known addition to the time interval to be measured increases the sensitivity. In the Boulenge chronograph the time interval to be measured is chosen to be of the order of 0·1 second while the disjunction time is 0·15 second. Thus the sensitivity is increased by a factor of 2·5.

$$\text{Now}\quad t = \sqrt{\frac{2h}{g}} - \sqrt{\frac{2h_o}{g}}$$

If the errors in measuring h and h_o be Δh and Δh_o respectively, we have

$$\frac{\Delta t}{t} = \left(\frac{\Delta h}{2\sqrt{h}} - \frac{\Delta h_o}{2\sqrt{h_o}}\right) \Big/ \left(\sqrt{h} - \sqrt{h_o}\right)$$

We see again that it is advantageous to have a larger disjunction time, i.e. a larger h_o, since for given h/h_o, Δh and Δh_o, the error is smaller, the larger h_o.

The maximum error in the above expression can occur if the two errors Δh and Δh_o have opposite signs. If we assume that $\Delta h = +\cdot 005''$, and $\Delta h_1 = -\cdot 005''$, we get

$$\frac{\Delta t}{t} = \left(\frac{\cdot 005}{2\sqrt{h}} + \frac{\cdot 005}{2\sqrt{h_o}}\right) \Big/ \left(\sqrt{h} - \sqrt{h_o}\right)$$

For a given h_o, the error is smaller, the larger the time to be measured (i.e. the larger h is) since the ratio $\left(\frac{1}{\sqrt{h}} + \frac{1}{\sqrt{h_o}}\right) \Big/ \left(\sqrt{h} - \sqrt{h_o}\right)$ is smaller, the larger h is. Thus if we require an accuracy of $0\cdot 1\% \left(\frac{\Delta t}{t} < \frac{1}{1000}\right)$ we can see from the above expression that for $h_o = 4\cdot 345''$, h should be at least $15\cdot 4''$, corresponding to a time of $0\cdot 13$ seconds for the projectile to cover the distance between the screens. The screen distance should be suitably adjusted for this, depending on the velocity of the projectile.

In adjusting for correct disjunction time, we make the cut made by the knife to coincide with a line already scratched. An error of $\cdot 005''$ at disjunction represents an error of $\cdot 00008$ second. This error in setting up the instrument will be reflected at each observation of velocity.

Next, the force exerted by the magnet on the rod does not change instantaneously to zero at break of the circuit but decreases at a finite rate depending on many factors. First, the force exerted by the magnet on the rods is initially adjusted to exceed the weight of the rod by about 10 per cent. Hence there is a delay before the magnetic supporting force is reduced to the weight of the rod, during which interval the rod remains stationary. Also, in the initial stage of its motion, the rod is still influenced by the decaying magnetic field and is thus not falling freely. Since both rods are affected, the errors due to the release of the two rods tend to cancel out; it is only the difference in the delay times of the two rods that introduces the error. This error is minimized by making the conditions as far as possible identical for the two rods. Both magnets are chosen to have the same form, size and number of turns. The currents in the coils are adjusted so that the forces exerted by the two magnets on the rods are equal. The interference in the initial rate of fall is minimized by proper choice of the time constants of the circuits, special attention being paid to the capacity and insulation resistance of the screen leads. (It has been found that an error of $0\cdot 04$ per cent may be caused by an error in current of 2 ma, a capacity variation of $\cdot 05$ μfd and a leakage resistance of $0\cdot 5$ megohm.) The time of release of the rod may also be varied by the presence of flats or dirt which may also affect the position of the hanging rod. The effect of air resistance on the motion of the rod can be neglected.

There may be variations due to the difference in tension or varying physical properties of the wire screen or difference in shape of the projectile. Flat-headed projectiles give better results than pointed ones. Errors may be caused when the long rod swings during fall since this may result in the variation of the throw of the knife before cutting. (A variation of 0·01″ in this throw will correspond to an error of 1 f/s in velocity).

In addition to the instrumental errors which are systematic, there may be random errors due to variation in time of operation of the knife. The adjustment of the disjunction, the setting of the magnet currents, the measurement of the distance between the screens and the readings of the velocity are other operations in which there is scope for errors, either systematic or random.

The accuracy depends on how the instrument is set up and manipulated. An accuracy of 0·1 per cent can easily be got with the Boulenge chronograph by taking all necessary precautions.

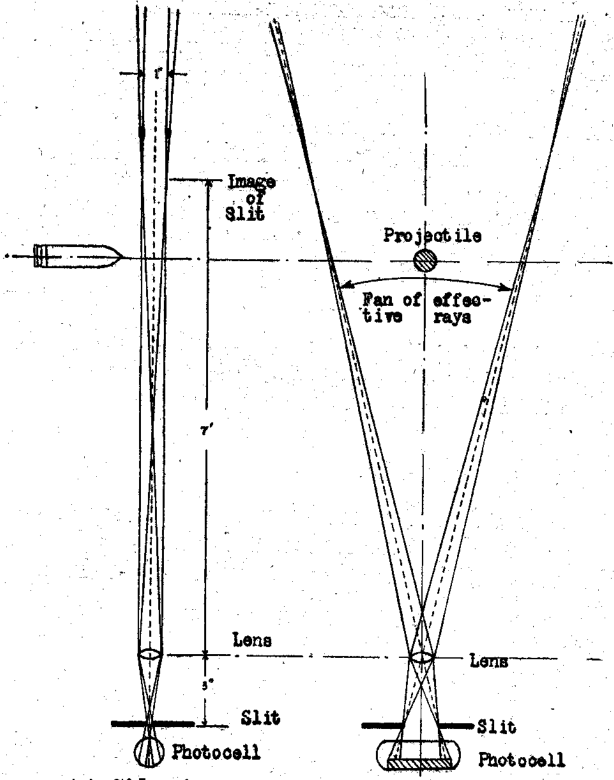
The instrument is easy to set up and manipulate. But there are objections associated with wire screens. Thus the instrument cannot be used with projectiles having sensitive fuzes, with very small projectiles or projectiles having long points. The screens interfere with the flight of the projectile and introduce sudden retardations. Portions of the screen may become attached to the projectile or trail with it for some distance. The wire may bend before breaking.

(c) *The Photo-cell Counter Chronometer*

The PCC has been developed during the past 15 years, especially by the Armament Research Establishment of the Ministry of Supply, United Kingdom and is now being increasingly used.

Here the base is defined by the distance between two photo cells and may be 50′ to 100′ or even less. The projectile cuts some of the light falling from the sky on the photo cells and two electrical impulses are produced, which are amplified and fed to the time-measuring instrument. The first impulse starts the instrument to count and the second stops it and the time interval is read off from the instrument.

The Photo cell—The photo cell which is especially blue-sensitive, receives light from a narrow region of the sky. A slit (1″×0·5″) is placed above the cell. A cylindrical lens of focal length 3″ is placed just over 3″ above the slit. An image of the slit is formed about 7′ above the slit and of the same size as the lens. The light reaching the cell is the beam shown in Fig. 2a, 2b. The beam has a width in this plane of about 1″. Since the focussing is done in only one plane, there is a wide fan of light of angle about 40° in the perpendicular plane. Thus the light reaching the cell has the form of a thin triangular laminar space, the field of view being narrow in the direction of the trajectory (to avoid errors in determining the distance between the two cells) but fairly wide in a direction perpendicular to the trajectory (so that the projectile can be aimed to hit the triangular lamina of light without difficulty). The projectile is arranged to pass as near the image of the slit as possible so that the maximum amount of light is cut off by the passage of the projectile.



(*a*) Side-view. (*b*) End-view.

FIG. 2

The variation in intensity of the light falling on the photo cell as the projectile passes through the field of view of the photo cell is shown in Fig. 3. AA′—BB′ represents the field of view of the photo cell. As soon as the projectile head comes to AA′ (point a in figure) the intensity of light falling on the cell starts decreasing and goes on decreasing until the projectile head reaches BB′ (point *b*). The intensity then remains constant until the projectile base reaches AA′ (point *c*). The intensity then starts increasing until the base leaves BB′ (point *d*) after which it remains constant. The variation in intensity for projectiles with ogival head is also shown in the figure.

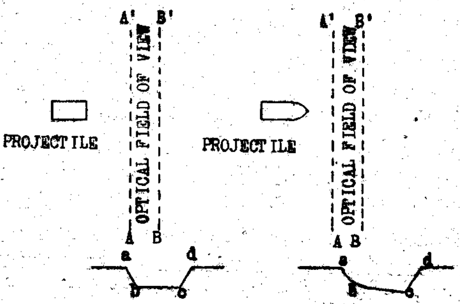


FIG. 3—Variation of intensity of light falling on photocell.

The photo cell units are placed on rails permanently fixed to concrete bases and they can be fixed at specified points on the rails in order to fix the distance between the units accurately and for providing a solid base for levelling. There are different suitable arrangements for elevation firings also. The rails are fixed so that the fields of view of the two photo cells are exactly parallel. In elevation firings this is specially important. In horizontal firings, this lack of parallelism is not a serious source of error since the shot passes very near the cells. The distance between the two cells, which is less than 100′, can be measured correct to 1/8″. The line of fire is vertically above the two cells and at right angles to the field of view, even though a departure of as much as 1° from the perpendicular direction will not seriously affect the accuracy.

In later types, the cylindrical lens is replaced by a number of spherical lenses. These produced slightly overlapping images of the slit. The spherical lens, being more free from aberration, gives more sharply defined images and there is less uncertainty in measuring the distance between the optical fields of view of the two photo cells.

Two electrical impulses of opposite sign are produced as the light on the photo cell is diminished and increased. Either of these may be used to operate the chronometer. For projectiles with ogival head, the impulse during the first part (when projectile enters field of view) is more gradual than the second part. In this case, it might be advantageous to arrange the signal due to the rear edge to operate the counter. But eddies at the shot base may make base registering less definite.

The electrical impulses must be amplified and fed without delay to the chronometer. Since the impulses may be of some 30 microseconds' duration, the amplifier must have a response up to frequencies greater than 35 kc/s in order to reproduce faithfully without delay the impulses.

Since it is convenient to keep the amplifier in the same room as the chronometer and sufficiently far away from the screens, the impulses have to be carried through cables to the amplifier. (To avoid delay due to transmission of impulses along the cable, the impulse from the photo cell may be arranged to trigger a VHF transmitter, which radiates through a directional aerial, the impulse being picked up by a receiver, amplified and fed to chronometer, thus doing away with the cables altogether). Now the cable has a low impedance while the photo cell may have an internal impedance of about 5 megohms. For impedance matching, a preamplifier is used to which the impulse from the photo cell is first fed. The output of the preamplifier which is kept near the photo cell unit is matched to the cable impedance and it is the output of the preamplifier (which has two stages and has an amplification factor of about 20) which passes via the cable to a 2-stage main amplifier situated in the control room. The main amplifier has a good frequency response up to 100 kc/s. A volume control is provided so that the gain can be adjusted to suit the prevailing conditions of light, the calibre of the projectile and the distance of the trajectory from the impulse unit. In some recent modifications, this correction is done automatically. The main amplifier output is fed to a pulse-shaping and triggering circuit (so that a narrow pulse with a steep leading edge triggers the chronometer).

The Chronometer—Wynn Williams in 1932 first described electronic counting devices. Uffelmann in 1937 suggested the idea of combining an electronic counting circuit with an oscillator to measure time.

The time interval required is measured in terms of the number of oscillations a quartz oscillator of accurately known high frequency (100 kc/s in PCC while there are commercial counters with 1 mc/s oscillators) makes in that interval. The oscillator is running continuously when the instrument is set up. There are switching circuits which are controlled by impulses supplied from external sources. When the first impulse from the external unit arrives to the switching unit, the oscillations from the quartz oscillator are suitably shaped and fed on to the counting unit which starts counting. The second impulse from the external source disconnects the oscillator from the counter which therefore stops counting. The number of oscillations made by the quartz in the time interval between the two external impulses may then be read off from the counter.

We shall describe here only the principle of operation of the scale-of-two counters, without going deeply into the circuit details. Such counters are now available commercially, which can count correct to a microsecond.

The scale-of-two counter—Consider the circuit shown in Fig. 4. Here the anode A_1, of the valve V_1, is connected through an R-C combination to the grid G_2 of the second valve V_2 while the anode A_2 of valve V_2 is similarly connected to grid G_1; by the grid bias batteries, E_1, E_2 the grids G_1, G_2 are arranged to have the same potential. They have zero grid bias to start with and the valves have a tendency to conduct.

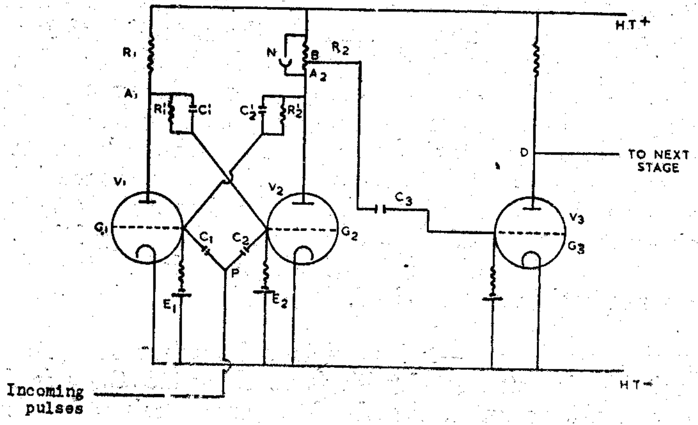


FIG. 4—Scale of two circuits.

Suppose V_1 is conducting. The current passes through R_1 so that there is an increased voltage drop across it. Thus the potential of A_1 falls and consequently the potential of G_2 also falls. So G_2 is made more negative than it was initially and by suitable choice of circuit constants, we can make the potential of G_2 so low that V_2 is prevented from conducting. Thus the circuit is stable with V_1 conducting and V_2 quenched. Similarly if V_2 starts to conduct when we switch on, the circuit takes another stable state with V_2 conducting and V_1 quenched. Which valve starts to conduct depends on the grid bias values. If V_2 is given an initial grid bias greater than V_1, it can be arranged that V_1 conducts initially. The grid bias batteries can then be adjusted to equality without disturbing the circuit.

Now let V_1 be conducting. If a momentary negative pulse is applied to P, this passes through C_1, C_2 and is applied to grids G_1, G_2. This reduces potential of both grids momentarily. But since V_2 is non-conducting, the current through it is unaffected and remains zero. The potential drop of grid of V_1 reduces the current through V_1. This in turn causes the potential of A_1 to rise and hence potential of G_2 also rises. So the bias of grid of V_2 is eliminated and V_2 starts conducting. This in turn applies a negative bias to grid G_1 and V_1 remains quenched. Thus the reception of a negative pulse changes the circuit from one stable state to the other. A second negative impulse will change the circuit again back to the original state. (Receipt of a positive impulse also tends to change the state of the circuit. But a larger positive than a negative pulse is required to accomplish this and circuit responds more readily to negative pulses). A neon lamp N placed across R_2 indicates by lighting up (due to voltage drop across R_2 when current flows through it) that V_2 is conducting. If now we arrange to produce a negative pulse every time V_1 starts to conduct, these pulses will occur with half the frequency of the incoming pulse. To do this and to couple this stage with another scale of two stage (to reduce the frequency of the pulses to $\frac{1}{4}$ the original frequency) the point B in R_2 is connected through condenser C_3 to the grid of Valve V_3 which is normally biased to cut off. When V_2 is quenched, potential of B rises and a positive pulse is applied to G_3 which makes V_3 conducting. Thus the potential of D falls and a negative pulse passes on to the next stage. If V_2 starts to conduct, the potential of B falls and a negative pulse is applied to G_3. But since V_3 is already biased to cut off nothing happens in this case. Thus for every two primary impulses, there is one impulse passed on to next stage. By thus coupling n scale of-two circuits, the number of pulses at the nth stage can be reduced 2n-fold. The last stage may be used to operate a mechanical counter, the number of stages being so chosen that the rate of reception of pulses at the last stage is slow enough to operate the mechanical counter. From the reading of the mechanical counter and observation of which of the neon lamps are glowing, we can find the number of pulses received.

The Scale-of-ten Counter—It is possible to have four sets of scale-of-two counters suitably interconnected (with feedback) so that the assembly functions as a scale-of-ten counter. A scale-of-two and a scale-of-five counter can also be combined to give a scale-of-ten counter.

The Switching Unit

The switching unit (Fig. 5) is connected to the first stage. Considering a scale-of-two circuit; suppose V_1—V_2 is the first stage. Initially V is conducting. So grid of V^1 and hence point, F and consequently the grids of V_1 and V_2 are negative to such an extent that chronometer cannot count. When the first impulse from photo-cell is received, V^1 starts conducting,

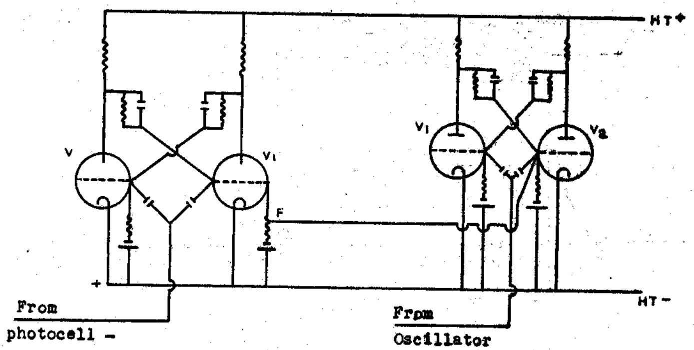


FIG. 5—Switching Unit.

F and grids of V_1 and V_2 get a high potential and they start conducting. So the valves V_1, V_2 change state at every oscillation of oscillator. Similarly chronometer is stopped when impulse from second photocell quenches V^1.

The Accuracy of the P.C.C.

(1) The P.C.C. works with a shorter base (the Australians use a base of 10′). There are also no contact screens which interfere with the flight of the projectile. (2) The distance between the two screens can be fixed correct to 1/8″ (error of about 0·1 per cent of 10′ base). (3) As far as the counting circuit is concerned, since the starting and stopping pulses may be received at any phase during one cycle of the oscillator, the maximum error is ±1 period of the oscillator. But it can be shown that the probable error is ±1/3 period of oscillator. Thus for a 100 kc/s oscillator, the maximum error is $\pm 10^{-5}$ second. If the time interval to be measured is 1/100 second, the error is less than 0·1 per cent. (4) Now the valve which operates the counter triggers when its grid potential is raised by a certain definite voltage. The delay in switching is determined by the time of passage of the projectile head through the beginning of the optical field of view and the instant when the voltage change produced at the photocell has been amplified to the necessary amount. This delay will depend on the change in illumination due to projectile, the sensitivity of the cell, the frequency response and the amplification factor of amplifier. If there is the same delay in both the impulse units, there is no error. But since we cannot ensure this absolutely, we try to keep the delay a minimum by proper choice of all the elements. If the leading edge of signal is used to operate the counter, the exact point on the leading edge at which counter is operated will, as mentioned above, depend on amplifier sensitivity. But since the voltage from signal will be several times that required to operate counter, we can be reasonably sure that the counter is operated well within the first half of leading edge of signal. The maximum error here, expressed as a space error is equal to the width of the field of view (1″). With ogival projectiles, the maximum space error is the width of field of view plus the length of ogive. But the probable error will be much less, about 1/8″. The maximum error can occur only if sensitivity of one amplifier is just sufficient to operate the counter while that of the other is far greater, which is very unlikely. Fig. 6 shows how the difference in amplification of the two amplifiers affects the measurement.

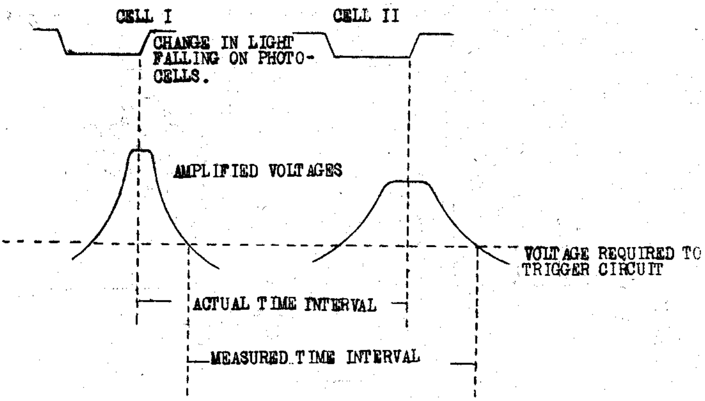


FIG. 6—Error due to varying amplifier sensitivities.

Assuming that the gain of the two amplifiers do not differ by more than 30 per cent, the effect of the delay will be of the order of 10 microseconds. (5) The noise level of the amplifiers must be very low, compared to the signal strength, to avoid faulty triggering. (6) There may be unbalancing of the stages in the circuit due to aging of valves and resistances. (7) Spurious signals due to microphonics, vibration of photocells, amplifiers and cables due to blast waves must be avoided. Thus the apparatus should be shock-proof. To avoid the circuit being operated by spurious signals, the circuits are designed so that they operate only once before being made ready for the next round.

Taking all precautions, the probable error of observation of MV with the P.C.C. can be reduced to about 0·03%.

(d) *The Solenoid Chronograph*

Here the projectile is magnetised before firing and in the trajectory are two coils of wire. An electromotive force is induced by the passage of the projectile through the centre of the coil. This impulse is used to actuate the time-measuring apparatus which may be of different types.

Thus the impulses after amplification by means of valves may be used to operate a Boulenge chronograph.

In the type of solenoid chronograph which is being extensively used in America, the two coils are connected to a Duddell type of oscillograph. There is a slit before the oscillograph through which light from a suitable source falls on the oscillograph mirror. The reflected beam passes through a shutter on to a photographic film on the surface of a rotating drum. There will be a straight band when there is no deflection of the galvanometer. The impulse from the coil will momentarily deflect the galvanometer which will be recorded by a break in the continuous band on the photographic film. For getting the time, a tuning fork of frequency 500 with two plates attached to its prongs is used. Twice in each cycle the slits will be in coincidence and permit the light from the same above source to pass through to the photographic film. Thus time marks will be made at intervals of 0·001 second. The time interval between the centres of the two breaks may thus be got. The apparatus can be modified to suit elevation firings also and there is no retardation of the projectile in flight. But the developing of the film takes time. The U.S. Naval Proving Ground oscillograph has an attachment which numbers and dates each strip before the record is made and another which automatically develops and fixes the record in a few seconds. The projectile may be magnetised by holding it in the field of a fixed coil carrying heavy current just before it is fired.

The impulses from the two solenoids have also been used to operate a counter chronometer of the type described with the P.C.C. But there are certain disadvantages. It is difficult to magnetise the projectiles uniformly. If irregularly magnetised, the e.m.f. induced in the coil is not of the standard type shown below, but very irregular. If the shell yaws appreciably, the e.m.f. induced in second coil may be very different from that in the first. If the number of turns of the coil is increased, the inductance and self-capacity also increase. This may lead to an oscillating circuit which distorts the voltage impulse. All these factors contribute to erratic operation of the circuit.

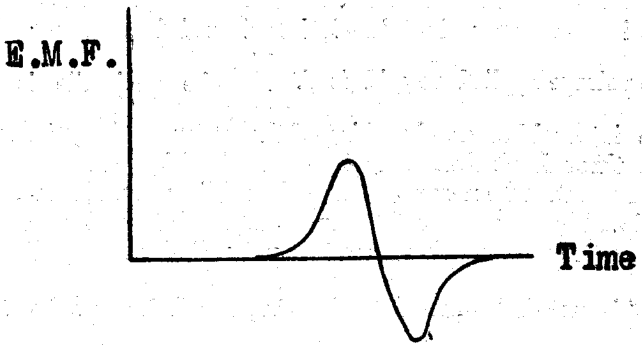


FIG. 7

(e) The Condenser chronograph.

The voltage developed across a condenser in the time taken by the projectile to pass between two screens is determined here, and from this the time calculated. Thus if we have the arrangement shown in Fig. 8 (with the switch in the 'a' position), when the screen S_1 is pierced by the projectile, C starts charging (until then S_1 is acting as short circuit) and when S_2 is broken the battery is cut off and further charging of condenser prevented. If the time taken by the projectile to travel S_1S_2 is t, v the corresponding voltage developed by C, and V the battery voltage, it is easy to see that

$t = RC \log\left(1-\frac{v}{V}\right)$. So by measuring $\frac{v}{V}$, we can get t.

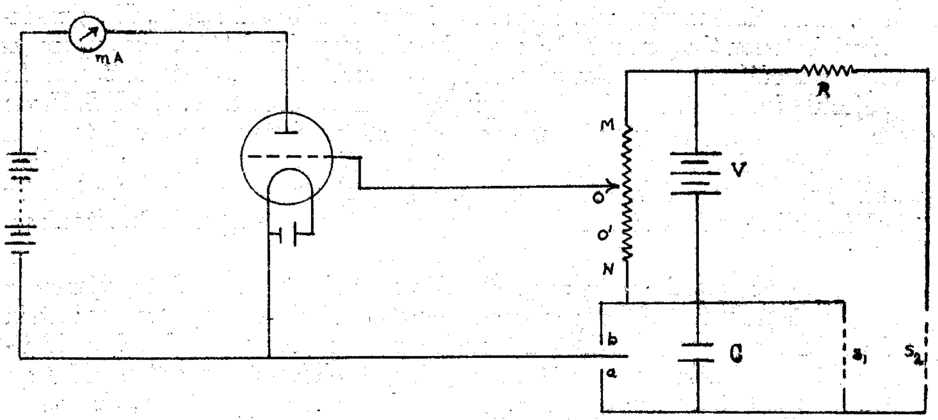


FIG. 8—The condenser chronograph.

In one of the methods applying this principle (the Weibel chronograph used by the British), v/V is measured by a valve voltmeter (Fig. 8). The voltage variation is applied to the grid of a triode and in the anode circuit is a milliammeter. There is a potentiometer wire across the battery. To use the instrument, the contact is moved to a point '0' such that the milliammeter reads a suitable value. The voltage applied to grid is $V.\frac{ON}{MN}$. The projectile is then fired. During the interval between breaking of the screens, the condenser charges and leaks through R thus reducing the grid bias and changing thereby the anode current. The new position of the milliammeter is finally noted. The switch is placed in the position b, thus isolating the condenser. The contact is now moved to another point o′ until some milliammeter reading is got. The distance oo′ is noted. $\left(\frac{v}{V}=\frac{oo'}{MN}\right)$. Knowing R and C, t may be found out.

For proper functioning, a high degree of insulation is necessary. Thus if S_1 remains conducting after circuit is broken, some charge leaks away. If S_2 remains conducting after second screen is broken, the condenser will continue to charge up. So the insulation resistance of the leads should be very high compared to charging resistance. There is a system of relays so that as the second screen is broken, the two screens are isolated from the instrument and no further leakage can take place. The instrument and leads should be kept dry.

The accuracy of the instrument depends on the accuracy of the valve voltmeter. The operation of the valve in the linear part of the characteristic curve gives the best results. The instrument can measure time intervals from 1 to 200 milliseconds with an accuracy of ±0·2 per cent and smaller intervals with slightly less accuracy. Frequent calibration of the instrument against a standard chronograph however is necessary. The instrument is self-contained, compact and portable and measures wide ranges of time. But the instrument has not been extensively used, except with small arms.

(*f*) *The Spark Chronograph*

This was originated by Werner V. Siemens in 1845 and has been used in Germany by C. Cranz and his co-workers Schmidt, Woehl and Schardin. It is also used in the Aberdeen proving grounds in America (where they call it the Aberdeen Chronograph).

Each screen consists of two thin metal sheets insulated from each other. This set up forms part of the primary of an electric circuit. A high voltage is induced in the secondary circuit, when projectile pierces the screen, which released a spark from a spark point. The spark is registered on a special roll of paper which is held on the inside of a rotating drum, held to the drum by centrifugal force. The spark electrodes are clamped on the inner side of the drum and are stationary. In the German type of instrument, the drum is rotated by a motor rotating at 6000 rpm. The motor may be a synchronous motor running at a constant speed. Variations from the specified frequency at the time of the experiment may be recorded by a frequency meter. As each of the two circuits is closed in turn by the passage of the projectile through the two screens, a spark jumps from the spark point to the paper. By measuring the distance between the two sparks and knowing the speed of rotation, the time can be got. The accuracy is about 0·8 per cent. The Aberdeen chronograph has a motor running at 1800 r.p.m.

(*g*) *The Kerr Effect Chronograph*

This has been used in Germany by C. Cranz, Kutterer, Schardin and others. The chief advantage here is the absolute freedom from time-lag in the registering impulse. The essential features of the method are shown in Fig. 9.

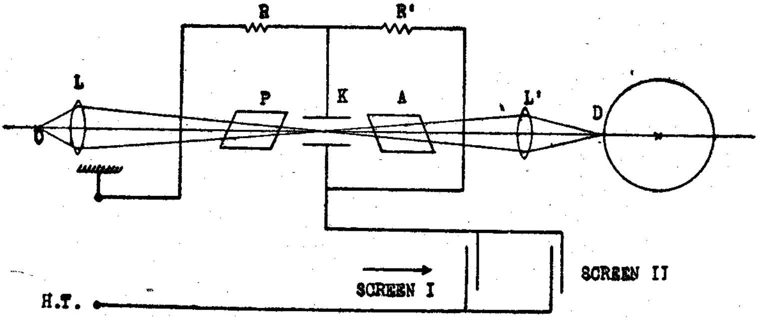


FIG. 9—The Kerr Effect Chronograph.

Light from the source 0 is condensed by the lens L and passes through the polariser P, the Kerr-cell K and analyser A. A sharp point image of the source is made to fall on the photographic film pasted on a rotating drum D. Initially the Nicols are crossed so that no light falls on the film. Due to the voltage impulse imprinted on the plates of the Kerr cell during the passage of the projectile through the first screen, light is momentarily allowed through and a sharp mark made on the drum. Similarly another mark is made when the projectile passes through the second screen. There are errors due to the shrinking of the film when it is developed, which may reduce the accuracy to 0·5 per cent. A modification is to do away to with the synchronous motor which drives the drum but to make the time marks directly on the film from a tuning fork. This eliminates error due to the film shrinkage and increases the accuracy.

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