Relay Measuring Equipment

By H. N. WAGAR

(Manuscript received September 25, 1953)

The wide variety of technical problems encountered in telephone relay design calls for quantitative measurements of many kinds, involving static performance and dynamic performance. The present article describes some of the more important measuring tools for this purpose, as used in Bell Telephone Laboratories. Instrumentation for evaluation of force, flux, displacement, time, or their combination, is described.

INTRODUCTION

Visitors to the switching development areas in the Bell Telephone Laboratories are often surprised at the extensive amount of measuring equipment used to study so simple a device as the telephone relay. This is because, though the relay itself may be simple, the problems requiring study are extremely complex. Because relays are used in such large quantities, their characteristics affect the economy of the telephone switching system. Not only is their manufacturing cost important; their quality also affects the central office cost. For example, an efficient design lowers the central office power plant cost, and faster-acting relays enable fewer common control units to handle more traffic, which further reduces the cost. These and related objectives pose many complex technical problems involving mechanics, magnetics, kinetics, heating, and the like.

The scope of relay analysis may be judged from the other articles in this issue. In every case there is need for measurement. Sometimes this quantitative work is needed to confirm an analytical relation, sometimes to learn more concerning the basic phenomena, and often to characterize the performance of a test model. This article will describe some of the most-used measuring tools for the study of relays.

Several kinds of measurements are required. In the first place, there are force measurements. Each relay must press the desired number of contacts together with a suitable force. To do this, a magnet must be provided which can move the springs, through whatever distance is required. Thus, measurement is needed of force-displacement characteristics—both for contact arrangements, and for magnets. Another field of measurement involves magnetics. Both the mechanical output and the electrical characteristics of the electromagnet are determined by its magnetization relations, requiring the measurement of magnetic flux. Beside such static measurements of mechanical, electrical, and magnetic quantities, corresponding measurements must also be obtained as functions of time in studying relay behavior under the dynamic conditions of actual operation.

The many instruments which furnish such data may be grouped into those for static measurements, and those for dynamic measurements. Some of these tools are described in the following pages, particularly as they relate to force, current, flux, displacement, time, or their combination.

STATIC MEASUREMENTS

The Measurement of Force

For a complete understanding of the operation of relay designs, knowledge of how the forces vary as the magnet air-gap changes, or as the contact members are deflected through their stroke, is of course required. The measurements most needed concern the force versus distance of the contact loads which the magnet must operate; and the force versus air-gap characteristic of the associated magnet. For many years, such measurements were made by a process of hanging weights and setting a micrometer screw, point by point, until complete data were obtained. More recently special instrumentation has made available a pendulum-type tensile tester,[1] and a spring balance device,[2] which have greatly increased the convenience of making these measurements, point-by-point. Today, however, many such measurements may be made still more conveniently by a machine which automatically causes the gaps to vary and plots a curve of force versus distance. Machines of this type have been developed to a high degree of flexibility for tensile testing of materials such as metals, plastics, textiles, or paper.

One such machine, which is extremely convenient for relay measurements, is the Instron tensile testing machine shown in Fig. 1. This machine is manufactured by the Instron Engineering Corporation of Concord, Mass. In conjunction with suitable current supplies to control the behavior of the relay magnet, and with a few special circuits for automatically correcting for flexure of the relay parts, and making other similar adjustments, this machine has proven eminently suitable for observing all "static" force-deflection characteristics of relays. The manner

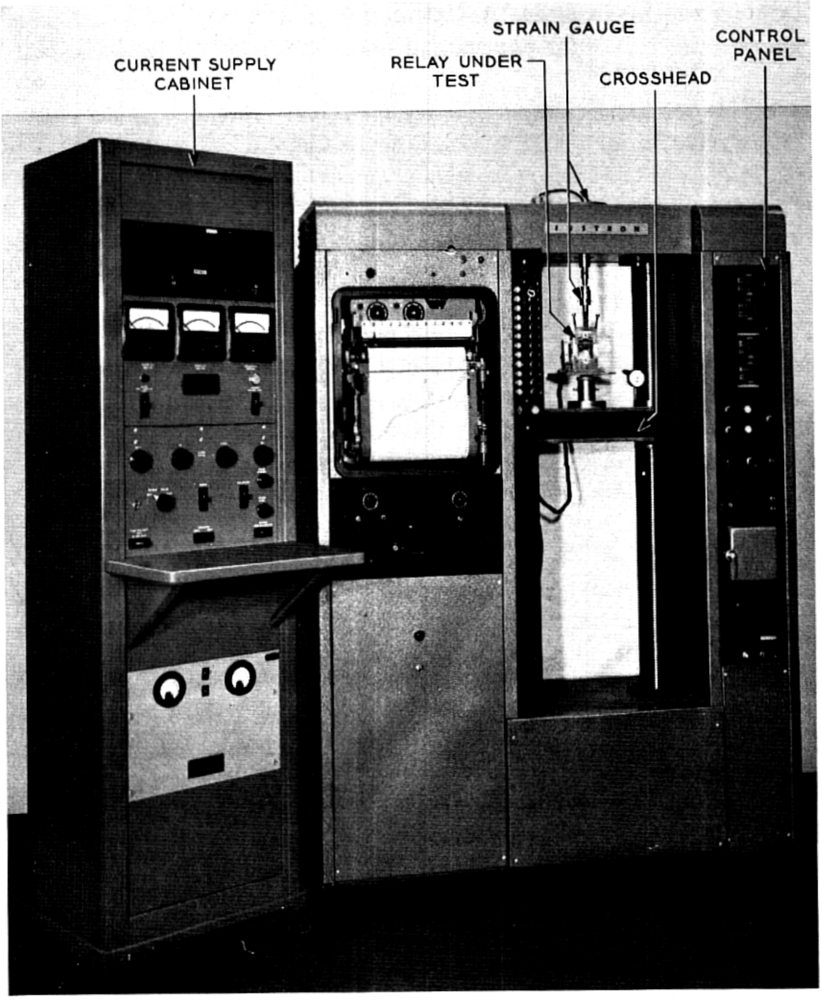

Fig. 1 — Tensile testing machine for force-displacement measurements.

of operation of this machine will be given only in outline as it is described elsewhere.[3] The force system to be measured, such as a relay magnet, is mounted on the crosshead of the machine, whose motion up or down may be controlled from the panel on the right. The other side of the force system being measured is connected to a strain gauge fastened to the top framework of the machine, and as the force on the strain gauge progressively changes, an electrical indication is given to the pen of the Leeds and Northrup X-Y recorder which then moves horizontally in proportion to the force. The crosshead motion is transmitted electrically to a servo system which drives the paper up or down in proportion to the displacement of the mechanism involved. Thus, during the motion of the crosshead, the pen moves proportionately to force, the paper moves proportionately to distance, and a force-deflection curve is drawn. As a result, the tensile characteristics of mechanisms can be recorded very easily. For example, force variations of relay springs or of relay magnets may be measured, or a combination of the two, as desired.

Some typical measurements obtained on this machine are given in Fig. 2 showing on one chart the manner in which electrical contacts change their force against the magnet and the manner in which the magnet pull varies across the gap. Such charts as these, when completely analyzed, enable the designer to choose the proper magnet for a particular spring requirement. Among the useful features of this machine are the accuracy of recording which readily provides one or two per cent accuracy, and the ease of tracing and retracing a particular measurement. Also readily obtained are exact information on the mechanical hysteresis losses within the mechanism. For example, in curve 1 of Fig. 2, the load characteristic of the contact springs is seen to have two values. The upper one represents the force on the closure stroke while the lower one represents the force on separation. The area between these two curves is the hysteresis loss; friction at any point is readily estimated as one-half the difference between upper and lower force readings. Special information, such as the exact location of first closure or first separation of contacts can also be included, as the machine is provided with a circuit to insert a "pip" on the record when desired.

This instrument has marked advantages because of its accuracy, speed, convenience and wide range of uses. With almost equal ease, mechanisms whose full force variation is 2 grams, and those ranging up to half a ton can be measured. Once a suitable jig has been prepared to properly mount the parts, the Instron machine will furnish a complete set of data in less than an hour, whereas by previous methods it would have required a matter of days.

The time required for each individual curve in the figure is the time allowed for the crosshead to move through the relay stroke. This usually is about 30 to 60 seconds, which adequately simulates the static characteristics of the relay force system; i.e., those force properties that would be measured at a particular point if the armature were held there. These static characteristics are commonly used in relay design to establish performance criteria for ordinary relays. However, in detailed studies of relay dynamics, these static characteristics must be supplemented by estimates or measurements of the inertia and other forces which also occur. The direct measurement of dynamic performance is described in a later section.

The Measurement of Flux

The mechanical output of a magnet depends on its magnetic quality. As is shown in companion articles in this issue, it is important for the designer to know the values of the closed gap reluctance $\mathcal{R}_0$, the leakage reluctance $\mathcal{R}_L$, and the effective pole face area A. Beside these important

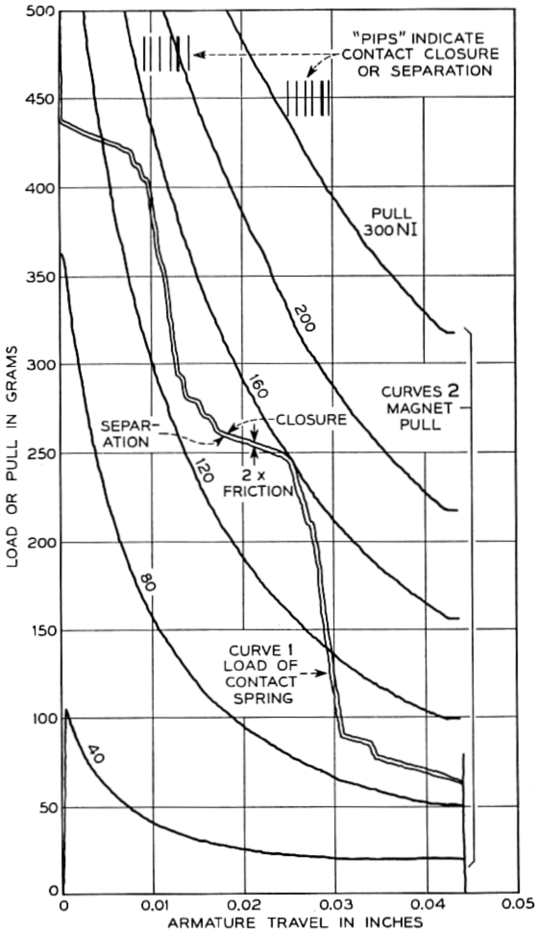

Fig. 2 — Typical recording of relay performance made on Instron machine.

figures of merit, values for saturation flux, φ'', and leakage flux ratios at various points in the magnetic circuit, are commonly needed. For such information, flux as a function of ampere turns must be measured. Perhaps the most effective method is to make determinations of the average flux in the magnet structure at a number of different air gaps; then by analysis determine values for the constants just enumerated. A series of magnetization curves for the relay magnet are required similar to those commonly taken on magnetic "ring samples," except that curves are obtained for several different air gaps. The ballistic galvanometer is the most familiar instrument for this purpose, still used for certain problems. In the Bell Laboratories, however, an extremely versatile recording fluxmeter was developed some ten years ago by P. P. Cioffi for use in research on magnetic materials.[4] One of these instruments is now in constant use for relay measurements because of its accuracy, versatility and the rapidity with which tests can be made. The complete unit is shown in Fig. 3, being made up of a power supply system, galvanometer-integrator unit, and X-Y recorder. Its operation will now be described very briefly.

The magnet to be tested is provided with a search coil. This search coil may be in the form of a winding physically in parallel with the main supply winding, a coil of few turns uniformly spread over the outside of the coil, or of a specially wound coil mounted at a particular point of interest. When current is progressively varied through the main winding, the voltage induced in the search coil by the magnet flux is transmitted to the galvanometer whose associated optical system divides a light beam between two photocells. The resulting photocell voltage unbalance is amplified and coupled back into the search coil circuit through a mutual inductance, so poled as to tend to restore the galvanometer deflection to zero. The feedback current in the mutual circuit is proportional to the flux, and is used to drive the pen on the X-Y recorder. The paper is driven proportionately to the current in the winding, with the result that flux versus current (or ampere turns) is plotted directly. The instrument gives accuracy of $\pm\frac{1}{2}$ per cent over a wide range of fluxes and currents, with provisions made for readily changing the scale to cover different windings, operating voltages or magnet shapes. Measurements are made in a few minutes compared to a considerably greater effort when using the ballistic galvanometer. Auxiliary features are also provided permitting convenient and complete demagnetization of the test magnets between readings. Readings are extremely stable and repeatable. Typical results are shown in Fig. 4 where a series of magnetization curves for a particular test magnet are shown. By

Fig. 3 — Recording fluxmeter.

methods of cross-analysis described in a separate article in this issue,[5] these data may be used to find the figures of merit for the magnet, and other information concerning its performance.

Often the measurement of magnetic potential at different locations in a magnetic circuit is required. Among the more versatile of such tools is the Ellwood magnetomotive force gauge.[6] A brief description of its operation appears in a companion article.[5]

The above measurements provide information on the static magnetic characteristics of a relay, but they do not provide all the information

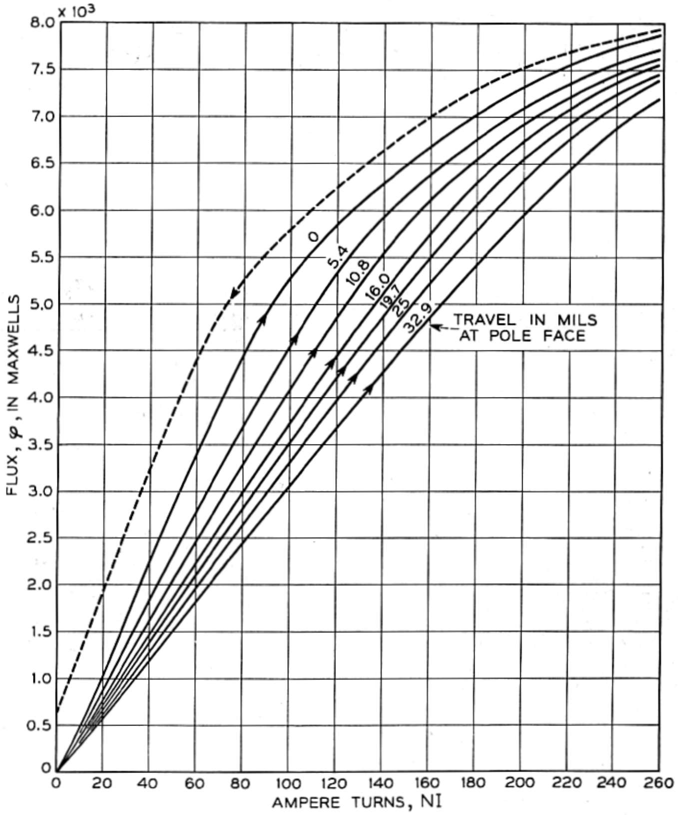

Fig. 4 — Typical recording of flux-ampere turn data on a relay magnet.

needed to describe the action while parts are in motion. For measurements involving dynamics, additional methods are described below.

DYNAMIC MEASUREMENTS

The measurements just described are indispensable in obtaining basic information on the relay's ability to perform its prescribed mechanical functions, which in turn depend upon its magnetic characteristics. They are needed in the every-day calculation of winding designs and the application of contact spring combinations which will be reliably operated by a given magnet. Cases arise in service, however, where very rigid requirements must be placed on closure and separation to insure the desired performance. Complete knowledge of the influence of voltage variations, mechanical adjustments, numbers of springs and their natural frequencies is needed. Often impacts and slide of parts must be minimized in order to reduce mechanical wear. Furthermore, the design of high speed relays requires an understanding of how the flux rises and decays when current is connected or disconnected.

For the experimenter in these fields, many tools are available covering measurements of force, flux, current, and time, or combinations thereof. These measurements may involve shadowgraph, high speed motion picture, or various transducer techniques, and many special methods; some of these are described below.

The Measurement of Force

There is a definite need to know how forces in a relay structure vary with time. It would, for example, be very useful to measure the force experienced by the relay armature as it presses against its spring load during operation. While a satisfactory measurement technique for this problem has not yet been found, there are a number of similar type measurements which can be applied to individual mechanical problems in the structure. For example, with the higher-speed relay functions of today, it is found that relays made by older methods suffer excessive

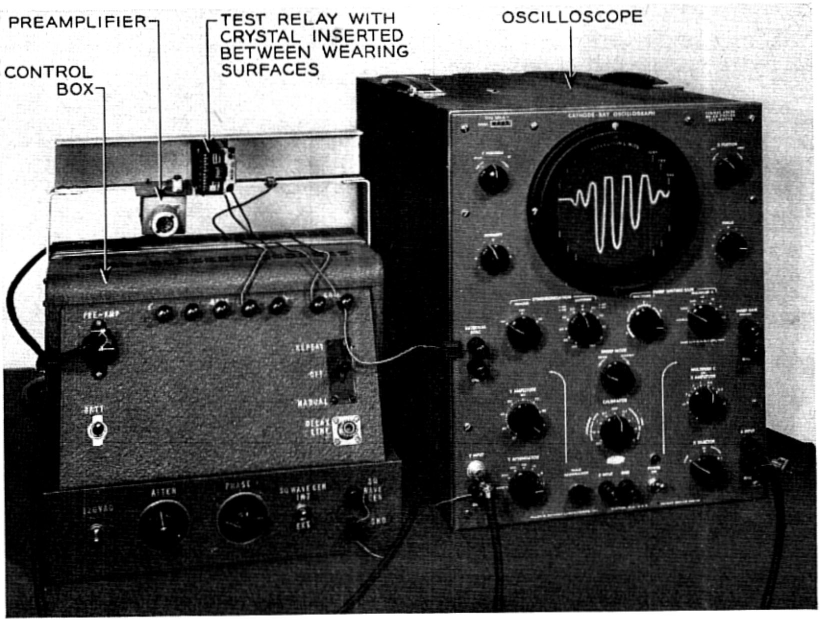

Fig. 5 — Barium titanate test set.

mechanical wear. In order to decide whether this is due to impacts, slide of parts, or vibration, methods have been developed to isolate some of the transient forces encountered in relay operation, and measure them individually.

Rapidly varying forces, such as impact forces, may be measured with the barium titanate crystal, which acts piezoelectrically to yield a voltage across its surfaces when subjected to compression or shear type forces. Since it can be obtained in very small sizes, it may be mounted within the relay as a substitute for the part to be studied. By observing the voltages that have been developed across it during relay operation, one may readily measure the forces involved.[7] Such an arrangement can be made to provide a faithful frequency response over a wide range, though it calls for careful amplifier circuit design. The unit shown in Fig. 5 provides for accurate frequency response for impact forces varying as high as 50 kilocycles. Fig. 6 shows a typical force-time relation obtained with this equipment. In some recent measurements on an experimental relay, the impact forces between the driving members were measured to be approximately five-fold the static force, but not sufficient to explain pulverizing and other damage to certain of the functioning parts.

Imposed Motion

Slide between parts has been found to be a very damaging source of wear in telephone relays. It has been studied in some detail by means of

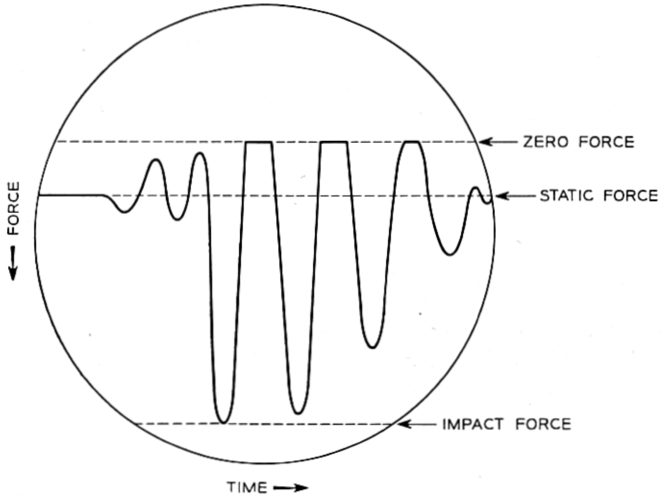

Fig. 6 — Oscillogram of impact in a relay.

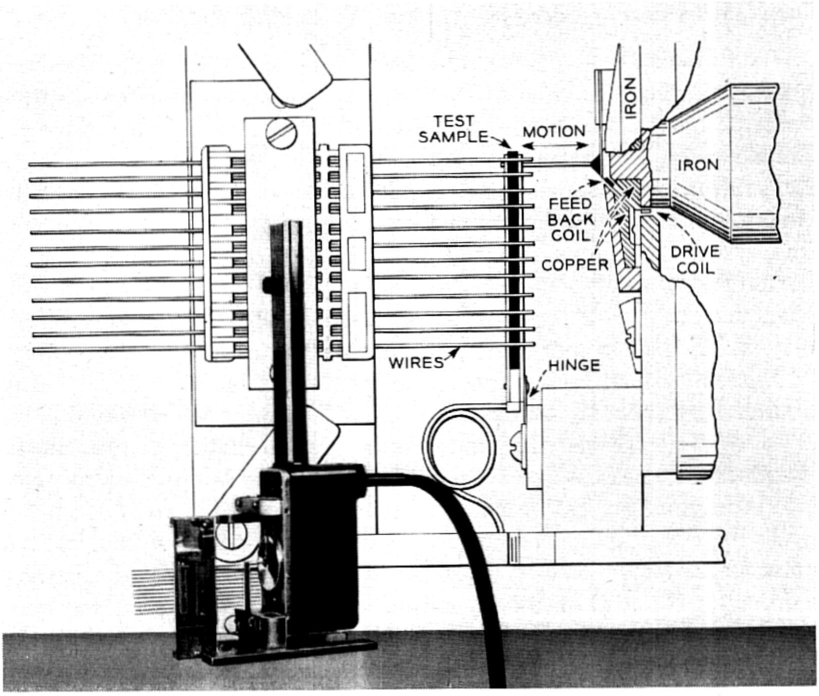

Fig. 7 — Photo of 1A recorder setup.

transducer elements whose motion is controllable to simulate a wide range of slide conditions typical of possible designs, from which wear measurements may be taken and analyzed. Such methods were also described in the previous reference.[7] The measurements may be made either by means of a barium titanate element or by means of a phonograph recording head such as the Western Electric 1A recorder. Because of the feedback coil and amplifier circuit, the latter transducer will generate the precise amplitude of motion desired for any particular test merely by properly setting its input current. It is normally driven at frequencies in the order of 1,000 cycles, permitting a large number of slides to be obtained in a short time and affording information to the designer on a very accelerated basis. Through the choice of different amplitudes, different materials to be tested, and different forces between them, a wide range of variables can be covered, to guide the designer in the proper choice of materials and conditions of use. A recorder setup for a typical test is shown in Fig. 7; data taken on a typical set of parts for an AF type relay are shown in Figure 8.

The Measurement of Flux

When attempts were first made to extend the speed performance of general purpose relays much below 8 or 10 milliseconds functioning time, it was found that the simplified eddy-current theory, which treated the core like a single short-circuited turn, was no longer sufficiently accurate. The subject has been clarified through the use of the dynamic fluxmeter which permits a direct determination of how the relay flux changes with time, under actual conditions. This fluxmeter, originally due to E. L. Norton and recently refined by M. A. Logan, was described in a previous issue,[8] and has proven most useful for determining those constants of the relay which the designer must understand in order to work much below 8 milliseconds functioning time. The instrument is shown in Fig. 9. It requires that the relay under test be pulsed, usually at a speed of about 10 to 20 cycles. When the main winding is alternately connected and disconnected, the search coil which surrounds the winding sends alternate positive and negative voltage impulses to a dc ammeter connected across its terminals. Now it can be shown that when the search coil and meter are disconnected during the interval from time zero to the moment of interest, then the resulting reading on the meter is exactly proportional to the flux at that moment. This switching function is provided by a timing circuit comprising a 40-kc frequency source driving a 3 decade counting ring, under control of switches permitting selection of the number of cycles of delay time. In this way the flux may be measured at intervals of 25 millionths of a second, with better than 1 per cent accuracy.

One interesting measurement has shown that in the short time intervals of present-day relays, eddy currents have less effect on the initial

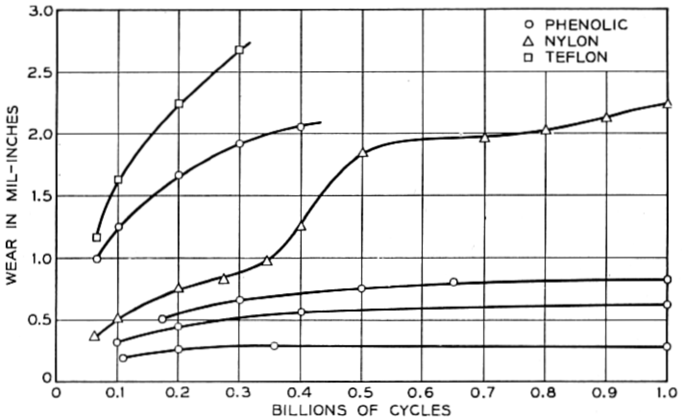

Fig. 8 — Slide data on AF relay.

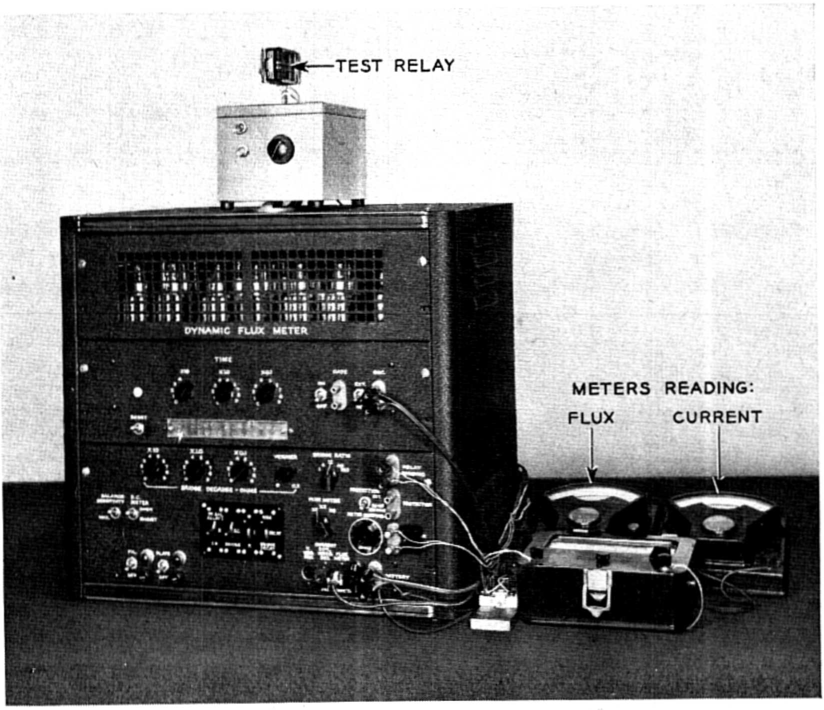

Fig. 9 — Photo of dynamic fluxmeter.

development and decay of the field than was previously thought to be the case.

The Measurement of Time — Electrical Effects

The actual functioning time of the relay is one of the more important behavior characteristics which must be tabulated for the particular design. Its measurement can be quite simple or quite complex depending on the problem involved.

One of the simpler time measurements is that permitted by means of the arrangement shown in Fig. 10. This particular equipment is composed of a control circuit for studying the various relay timing conditions, and a Berkeley Timer made by the Berkeley Instrument Company. The timer is provided with electronic controls which cause it to start counting cycles from a standard frequency when given an electrical impulse and to stop counting upon receiving a second impulse. The circuit may be arranged to give the first impulse when the relay winding is connected or disconnected and the second impulse when the contacts or other

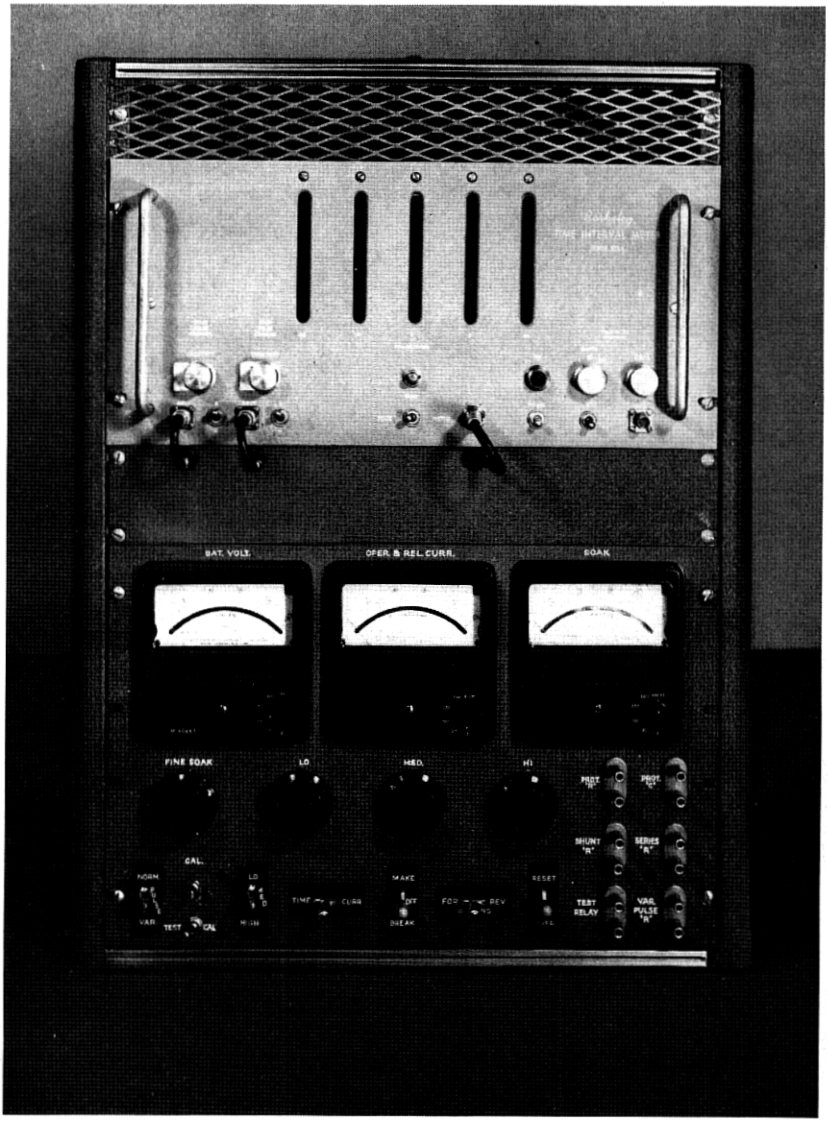

Fig. 10 — Photo of timing setup.

members either touch or separate. It is timed by a 100-kc oscillator allowing measurements to be made at intervals of 10 millionths of a second. It is in constant use for the every-day measurement of relay timing.

The simple timing measurements just described afford data on the basic timing characteristics of the structure, but may give insufficient information on the timing performance of the relay contacts in a particular circuit. For example, contacts may close as desired but then reopen intermittently in a manner to cause either unwanted circuit behavior or undesirable contact sparking and consequent erosion. Sometimes the relay armature, in crossing the air-gap, encounters sudden loads as springs are successively picked up in the stroke, causing it to momentarily reverse its direction before pulling home. Also, when the relay armature releases, it may strike the backstop and rebound, recrossing a portion of its gap and causing undesirable reactuating of the contacts. Such momentary opening and closing of the contacts is classed as "contact chatter," and special means are needed to detect, measure, and understand its behavior.

The string oscillograph has been extremely useful for recording and studying such timing effects when the contact chatter was of comparatively long duration and low frequency. For relays whose functioning time exceeded 10 milliseconds and where chatter intervals were in the order of 2 or 3 milliseconds each for possibly 6 or 7 successive times, this instrument was most effective. For many of the faster relays, however, where chatter of this type has been completely eliminated, there remain problems of much higher frequency, shorter duration chatter, which are still of great importance to the circuit designer. In such cases the cathode ray oscilloscope is used.

A cathode ray oscilloscope arrangement for the study of chatter is shown in Fig. 11. The horizontal axis of the oscilloscope has a calibrated time base and the trace is displaced vertically to mark closing of the contacts or other events of interest. The horizontal sweep may be triggered at the initial closure of the contacts, but a variable time delay

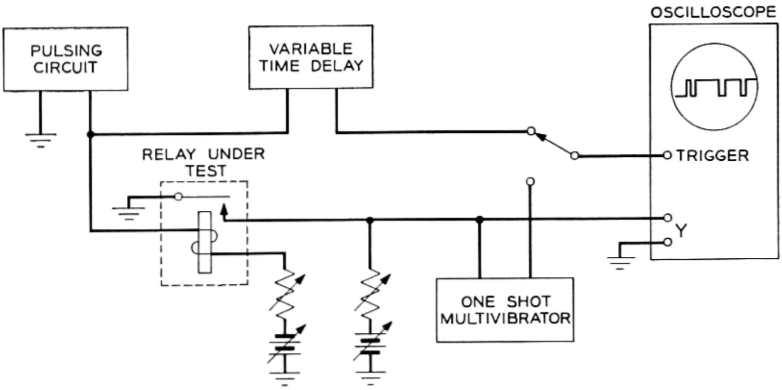

Fig. 11 — Cathode ray oscilloscope circuit for the study of contact chatter.

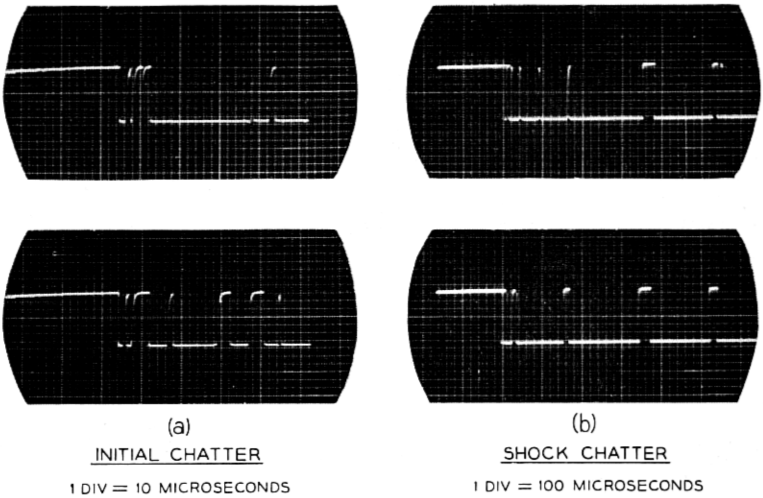

Fig. 12 — Views of chatter obtained by oscilloscope.

can be used to trigger the sweep at a later time so that any portion of the chatter can be observed in detail. Typical measurements are shown in Fig. 12. In each of the views, the horizontal lines starting at the upper left represent open contacts, the lower horizontal lines represent closed contacts, and any jumping between them indicates chatter. Fig. 12(a) shows the relatively high frequency chatter which occurs immediately after contacts close. This is called initial chatter and is caused by vibration of contact springs in their higher modes due to the impact of mating contacts. Initial chatter differs in character from the lower frequency shock chatter shown in Fig. 12(b). Shock chatter is caused by wire vibrations induced by the shock of the armature striking the core. The time of each reopen of the contacts and the time between opens is much longer than for initial chatter.

Many measurements of the type just described are made in the course of a relay development. They enable the relay designer to relate chatter performance to design characteristics of relays so that contact chatter can be reduced or eliminated. Such measurements also allow one to classify chatter performance according to the circuit application.

The Measurement of Time — Mechanical Effects

Electrical timing measurements previously described give data on over-all effective performance; to understand these results one often needs to measure displacement-time characteristics both alone, and in relation to current versus time and flux versus time. The string oscillo-

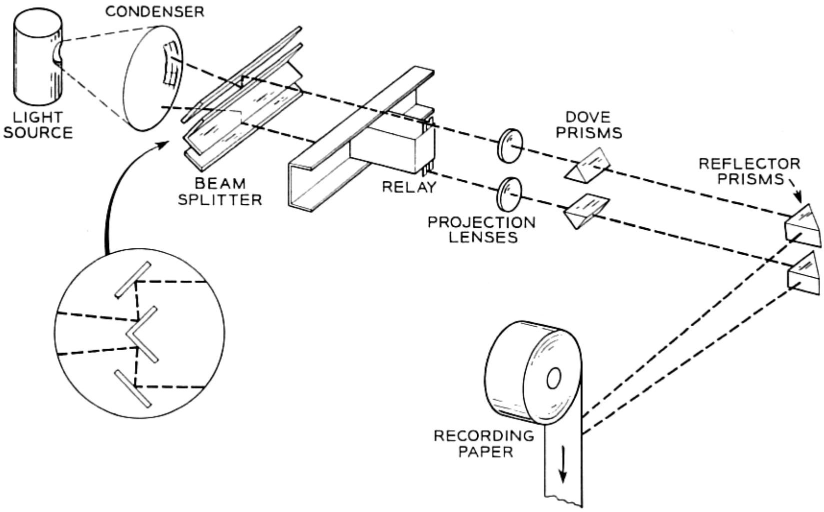

Fig. 13 — Schematic of shadowgraph action

graph mentioned above, has on many occasions been modified to also record a silhouette of the moving parts of the structure on a moving strip of photographic paper, and thus provide a simultaneous trace of displacement and current against time. One of the more advanced shadowgraph-oscillograph equipments is shown in Fig. 13, and a typical record made on a wire spring relay is given in Fig. 14. In this case the single record shows the current to the winding and the mechanical movement at the two opposite ends of the contact-operating card attached to the armature of this relay. From such measurements, velocities of impact, location of the parts at a given instant, stagger between parts, relative motion, unbalanced motion, and the like, may all be determined and correlated with electrical changes.

Motion of parts may also be studied optically to give displacement or velocity data, using the photocell. Properly placed flags on the moving

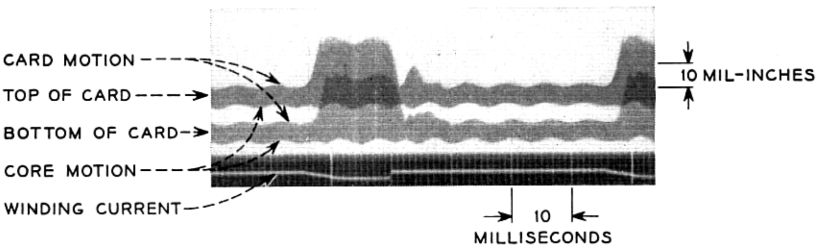

Fig. 14 — Typical shadowgram of 287 relay armature motion.

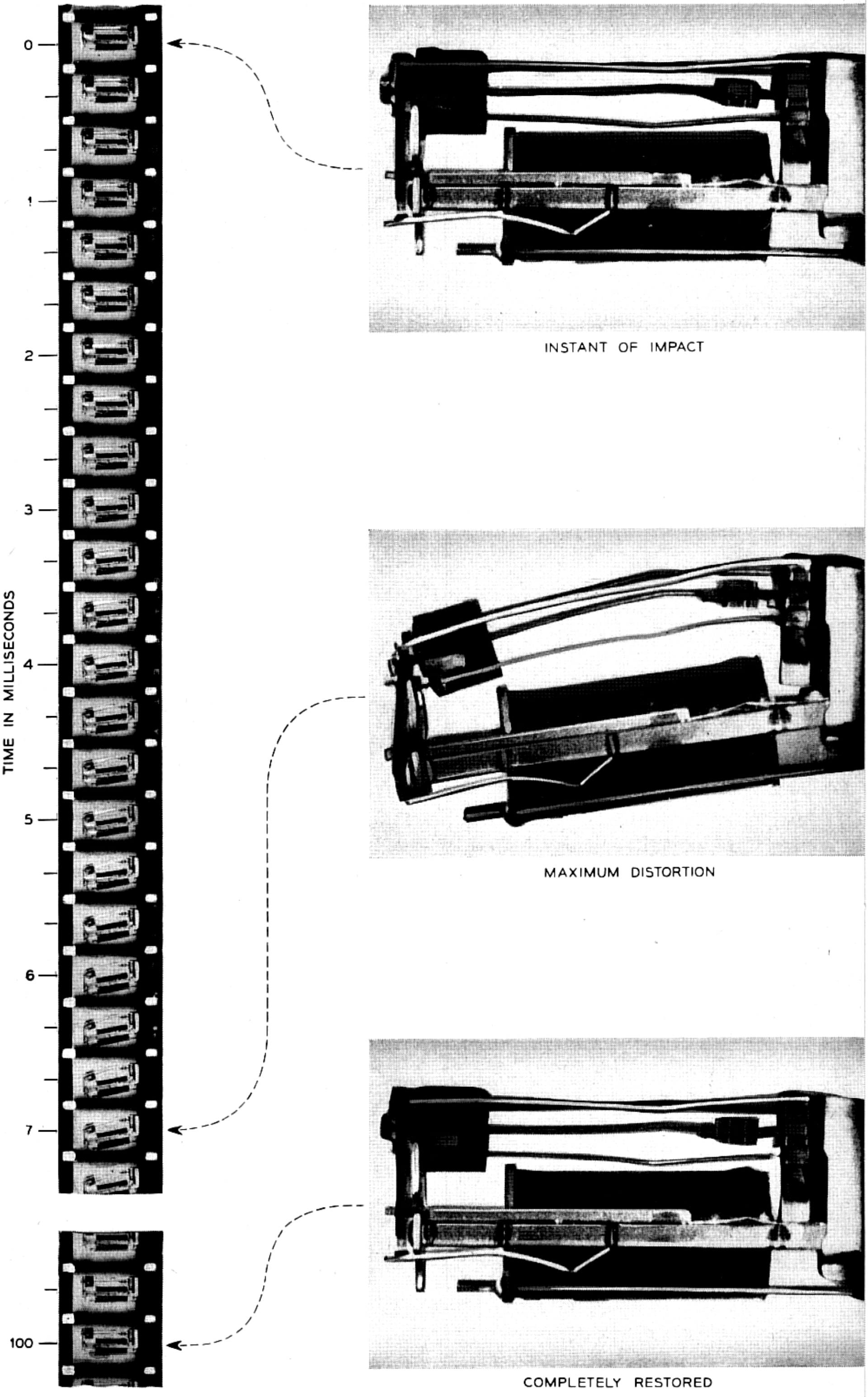

Fig. 15 — High-speed motion pictures of a falling relay at the moment of impact.

parts of the structure control the light falling on the cell, whose output can then be converted so as to read directly as displacement. The displacement data may then be differentiated as a function of time, in electrical differentiating circuits, to give very accurate measurements of velocity. A complete description of this method, originally due to E. L. Norton, has been published by M. A. Logan.[8] As a result of the accuracy and convenience of this method, it has recently been used extensively in relay studies correlating the amount of contact chatter with armature velocity.

The motion of parts may also be observed with various forms of transducers. One which is now finding application in telephone relay studies is a type of electrostatic gauge, measuring armature displacement by the changes in capacity between it and a fixed electrode. The entire scheme is to be described by T. E. Davis and A. L. Blaha in a forthcoming issue.

Some relay motions need to be studied in three dimensions. Then the high-speed motion picture gives best results. By photographing at up to 5,000 frames per second, and viewing at about 20 frames, a time magnification of 250 to 1 can be gained. If need be, such pictures may be scaled off to give displacement-time information, a somewhat tedious task. A recent study of the effect of dropping in shipment gives a striking picture of the utility of the method Fig. 15 gives views, photographed at 3,000 frames per second, of an AF relay as its mounting plate strikes a concrete block at the end of a six inch fall. Severe distortion, followed by recovery of the parts to normal, may be seen. With such information, relay designers can plan parts to stand the service stresses, and form a clear judgment of the margin of reliability built into the structure.

CONCLUSION

Although the relay is one of the oldest devices in the telephone business, many features of its operation are still imperfectly understood, even today. The number and complexity of the continuing technical problems may be judged from the other articles in this issue, on representative relay subjects. As improved relay operation becomes ever more important in the telephone system, the analytical and measuring technology for these devices must progress, in parallel. Some of the typical measuring equipment, as needed for modern relay design, has been described in this article.

REFERENCES

1. R. L. Peek, Jr., Measuring the Pull of Relays, Bell Lab. Record, June, 1953.
2. T. E. Davis, Measuring the Load-Displacement in Relays, Bell Lab. Record, June, 1953.

3. G. S. Burr, Servo-Controlled Tensile Strength Tester, Electronics, May, 1949, and E. G. Walsh, Continuously Recorded Relay Measurements, Bell Lab. Record, Jan., 1954.
4. P. P. Cioffi, Recording Fluxmeter of High Accuracy and Sensitivity, Rev. of Sci. Instr., July, 1950.
5. R. L. Peek, Jr., Analysis of Measured Magnetic and Pull Characteristics, page 79 of this issue.
6. W. B. Ellwood, A New Magnetomotive Force Gauge, Rev. Sci. Instr., **17,** p. 109, 1946.
7. W. P. Mason and S. D. White, New Techniques for Measuring Forces and Wear, B. S. T. J., May, 1952.
8. M. A. Logan, Dynamic Measurements on Electromagnetic Devices, B. S. T. J., Nov., 1953.