STUDIES IN SOIL CULTIVATION. IV.

A NEW FORM OF TRACTION DYNAMOMETER.

BY W. B. HAINES AND B. A. KEEN.

Soil Physics Department, Rothamsted Experimental Station.

(With Two Text-figures and Plates XII and XIII.)

INTRODUCTION.

IN the first paper of this series (1) a description was given of the Watson dynamometer, which was employed for certain developments in the application of dynamometer technique to problems of soil cultivation, described in the second and third papers (2). For the continuation and extension of the experiments to different types of work it became very necessary to employ a dynamometer more adaptable than the original. This was designed for tractor ploughing, when the line of draught between tractor and plough was close to and fairly parallel with the ground surface. The higher and sloping line of draught employed in horse traction rendered the Watson dynamometer useless for extension to this kind of work, and in any case it was much too heavy for the purpose. It was also desirable to improve the method of recording the draught, which required constant and careful attention, especially in adverse conditions. A new dynamometer evolved to overcome these objections is described in the present paper. It is very light and portable, but of robust construction, and by a simple adjustment can be made to cover all ranges of draught from the heaviest to the lightest with the same percentage accuracy. The number of moving parts is very small and adjustments for stylus pressure, etc.—an inconvenient and frequent necessity with other instruments—are very rarely necessary. The system of recording employed is quite unaffected by weather or soil conditions. The apparatus has been very fully tested, and has been found very satisfactory. Its adaptability for different types of work is shown by its use at Rothamsted for horse ploughing investigations and, in India, for heavy mole drainage trials. It has been placed on the market by the Cambridge Instrument Company.

DESCRIPTION OF THE DYNAMOMETER.

The dynamometer consists of three main parts: (*a*) a hydraulic link, in the form of a piston and cylinder containing oil, placed in the hitch of the implement; (*b*) the mechanism that records the fluctuations of pressure on the oil as the implement is drawn forward; (c) control box, carried by the operator.

Copper tubing containing oil is used to transmit the pressure in the hydraulic link to the recording mechanism. The tubing is coiled in a spiral, so that alterations in the relative positions of link and recorder during work can occur without any strain on the apparatus. This arrangement also allows the recorder to be disposed in any convenient position.

The general arrangement of the constituent parts is shown in Pl. XII, fig. 1, and diagrammatically in Fig. 1. Referring to the figure, the hydraulic link *A*, is shown on the left. No serious disturbance is produced in the

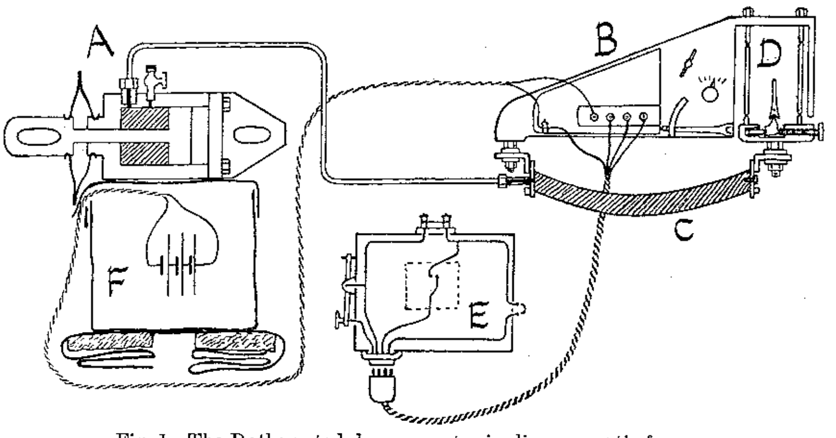


Fig. 1. The Rothamsted dynamometer in diagrammatic form.

line of draught when this is introduced into the hitch of an implement as its weight is only 16 lb., and the extra length entailed (about one foot) can, if necessary, be compensated by removing a few links from the hitch chain. A hollow leather collar is fixed over the end of the cylinder and the protruding portion of the piston, to prevent the entry of dust and water. The pressure is transmitted through the oil in the flexible copper tubing (not shown coiled in the diagram) to a Bourdon tube (*C*) also containing oil, and bent into the arc of a circle. The variations in oil pressure produce changes in the curvature of the arc, and in consequence, alterations in length of the chord. This change of length is very small, and is therefore directly proportional to the oil pressure, and thus to the soil resistance. The change of length is magnified and recorded by the mechanism *B* which is the well-known Stress Recorder manufactured by the Cambridge Instrument Company. The Bourdon tube is rigidly bolted at its left-hand end to the frame of the Recorder, while the right-hand end is bolted to a floating stage. Three interchangeable Bourdon tubes are provided, of different strengths for use in light, medium and heavy work, respectively. The floating stage is supported by three steel pillars whose diameter is reduced at the points shown, to allow the stage to move to and fro in response to the extension and contraction of the Bourdon tube. This movement is magnified and transmitted to the recording arm *D* by a simple and robust system of two knife-edge levers. Attached to the upper portion of the arm is a very small rounded stylus, pressing against a celluloid ribbon 11 mm. wide that is advanced continuously by clockwork within the recorder casing. The speed of the clock can be varied within wide limits by turning an indicator on the recorder, and it can be started or stopped by an electrical control. The stylus does not scratch the celluloid, but causes it to flow plastically, so that the trace is impressed in the form of a grove bounded on each side by a small ridge. The line of zero draught can be adjusted by the small milled-head shown on the right of the floating stage, while the pressure of the stylus on the celluloid is adjusted, if necessary, by a second screw, not shown in Fig. 1. This method of recording has very great advantages, for the trace is permanent, and is unaffected by oil, dirt, or water. If necessary the celluloid ribbon can be cleaned by dipping it in water and wiping it dry with a cloth.

The small movement of the floating stage and the simple lever system of magnification result in the movement of the recording stylus being proportional to the stress applied to the hydraulic link. Direct calibration curves connecting stylus position and stress were obtained by suspending the link vertically, adding equal increments of weight up to the maximum, and then reducing the load by equal amounts to zero. The calibration curves for increasing and decreasing stress were linear, and identical.

In addition to the stress-recording stylus there are two others, that operate on the back of the ribbon, to avoid fouling the main stylus. One is used for recording time intervals and the other for position marks, and both are controlled electrically.

The three controlling circuits—clock for chart movements, time-recording clock, and position-recording key—are governed from the control box *E*, weighing only 4 lb., and carried in a light harness by the operator. The box carries (*a*) a switch for starting or stopping the chart, (*b*) a clock that momentarily closes, at ten second intervals, the circuit operating the time stylus, and (*c*) a tapping key for closing the circuit operating the position stylus. The tapping key is used for recording position marks, passage from one plot to another, etc., and for marking on the chart in the Morse code any other details of importance. This feature is valuable: not only does it eliminate any possibility of confusion when the records of a complicated experiment are examined in the laboratory, but it also serves for recording important notes on the soil conditions, the behaviour of the implements, etc., that would otherwise have to be entered in a notebook while the experiment was actually in progress.

The three circuits have a common return wire, and are brought out to the four terminals of an ordinary wireless valve holder, so that a convenient and automatically correct connection can be made through a four-pin plug to the cables from the recorder. The cables are joined into one strand and lightly armoured for protection. The current for the circuits is provided by a six volt battery *F*, that can be carried in any convenient position. The low internal resistance type of dry battery is quite suitable for the purpose. In Fig. 1 and Pl. XII, fig. 1 they are shown in a leather case, riveted to a surcingle so that they may be carried on the back of the horse. For tractor ploughing the batteries would be carried on the tailboard, in which case they would be more conveniently connected to the two terminals shown on top of the control box.

A direct reading pressure dial gauge can be introduced if required into the oil system at any convenient point, or can be attached to the hydraulic link in place of the copper tubing and the recorder. Two such gauges, for heavy and light work respectively, and calibrated to give directly the pull applied to the hydraulic link, are shown as part of the dynamometer accessories in Pl. XII. Its main use is for purposes of demonstration, or for the securing of preliminary information. The limitations of a direct reading gauge as compared with a recording device are discussed later.

ASSEMBLY FOR FIELD WORK.

The method of assembly for field work is as follows. The hydraulic link is connected into the hitch, and the stress recorder, which weighs only 15 lb., is strapped in any convenient position on the implement, *e.g.* the beam of a plough, or the frame of a cultivator, care being taken to pad it with a roll of felt against mechanical shock, since the stylus responds to such vibrations. The Bourdon tube must also be unrestricted, and not liable to any casual contact with the implement. The link and the recorder are then connected by the spiral of copper tubing. This is provided in fairly short lengths with screw unions so that it can be easily adapted to varying dispositions of the link and recorder. It is also necessary to tie down the tubing to some support at a short distance from each of the two ends, so that strains produced when turning at the headlands are not concentrated at these points but properly taken up in the spiral part of the tubing.

The whole system is then filled with oil from an oil-gun. The batteries are mounted, and if necessary the cables tied with string to suitable points to prevent them from dragging on the ground or fouling the implement. The operator then straps on the control box, inserts the four-pin plug into the socket and gives the signal for work to begin.

A photograph of the dynamometer in use for horse ploughing is reproduced in Pl. XII, fig. 2.

The operator walks beside the implement, using the tapping key to record on the chart the points of passage past pre-arranged points. For the general work, these points are previously fixed by stakes placed in the ground at suitable places. The tapping key is also used, as previously mentioned, for Morse code notes of the work.

The celluloid ribbon passes out through a slot in the recorder, and convenient lengths of it can be cut off at intervals. A low power microscope is provided in the kit, so that the record can be examined in detail to check the correct functioning of the recorder. The portability of the complete equipment may be judged from Pl. XIII, showing it packed for transit, in a strong oak box, of outside dimensions $21 \times 15 \times 14$ in. The total weight, including spare oil, tool bag (carried in the box but not shown in the photograph) is under 100 lb.

Laboratory Examination of the Records.

The examination and reduction of the records is done in the laboratory. The trace is too small for direct integration, so this process must be carried out on enlarged copies. The optical properties of the groove and flanking ridges that constitute the actual trace on the celluloid give rise to a very clear and sharp magnified image, that can be taken on sensitive paper, or copied by hand. In many uses of the Stress Recorder, requiring an intensive examination of the stresses during a short interval, the photographic method of enlargement has been found best. But the nature of the problem in soil resistance measurements is quite different. Although minor fluctuations in resistance can be recorded with great fidelity, their exact significance refers primarily to the occurrence of stones in the soil, to the gait of the horses and other casual factors,

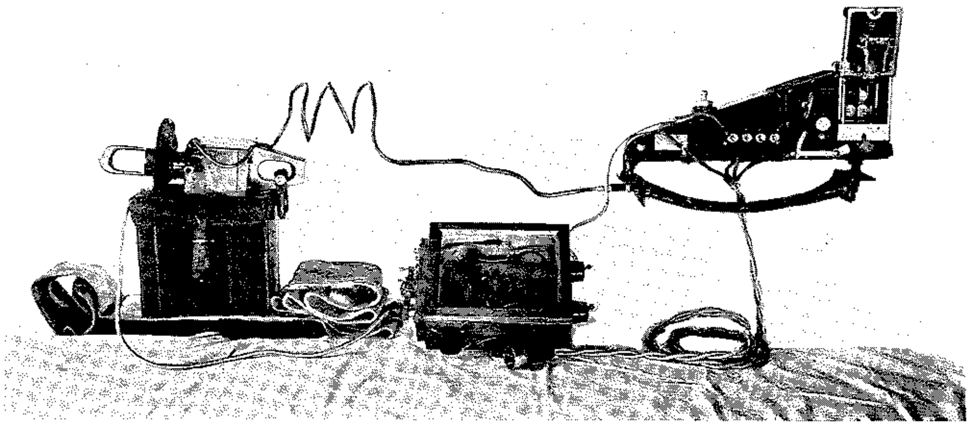


Fig. 1. The Rothamsted dynamometer, showing the units assembled.

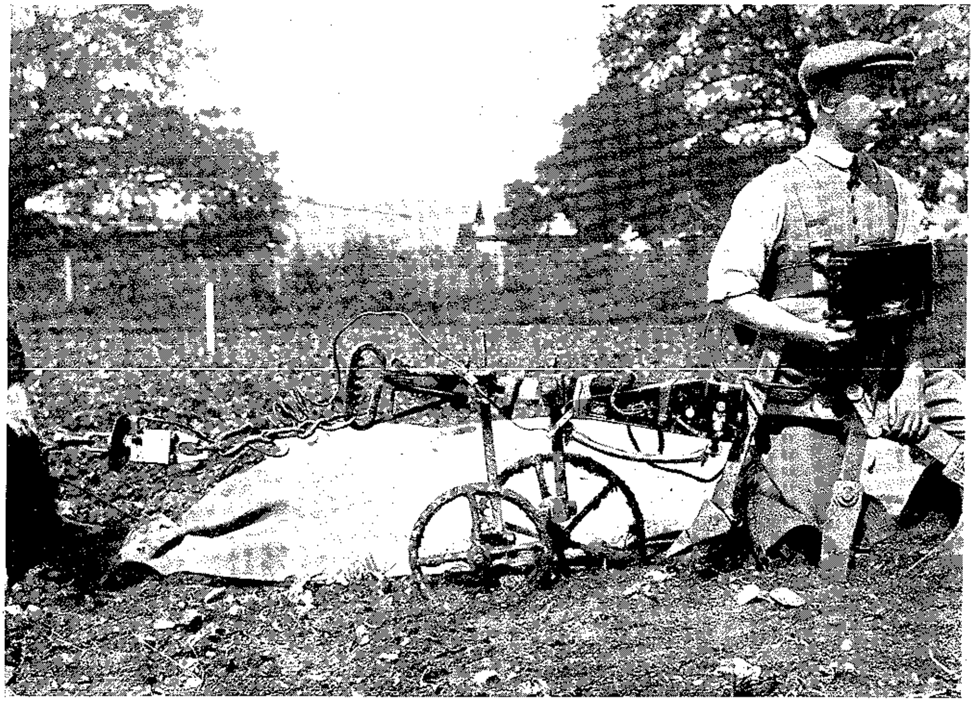
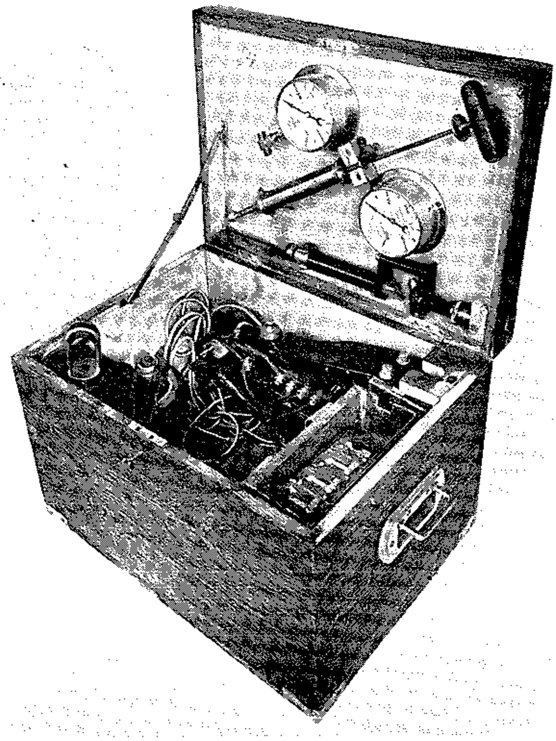


Fig. 2. The dynamometer as arranged for horse-ploughing measurements.



Showing dynamometer and accessories packed for transport. Total weight less than 100 lb.

whereas the present interest of the results for soil research lies in the mean values of soil resistance obtained from extended records.

The method we have adopted is to use a low power microscope and camera lucida to transfer an enlarged image (× 34) of the trace to paper, after which it can be divided into its sections as shown by the position marks, and the mean stress of each section calculated by integrating the area with a planimeter, and applying the linear calibration factor. The chart is fed, a step at a time, between two glass plates, mounted a short distance apart, that serve to keep it flat and retain it in position.

With the ribbon speed employed in horse work it is possible to get two adjacent sections of the trace, each representing about twenty-two yards of ploughing, into the field of view at the same time.

THE CHARACTER OF THE RECORD UNDER DIFFERENT CONDITIONS.

The whole question of the amount of detail to record in the stress fluctuations either on the trace itself, or in the enlarged copy, requires some judgment to obtain the best results. The instrument is capable of recording stress fluctuations in full detail, if filled with thin oil, and run with a chart speed high enough to open out the trace. Conversely the fluctuations in the record may be smoothed or damped out to any required extent by the use of thick oil, and by introducing a needle valve constriction in the copper tubing. Damping, however, makes the instrument sluggish, and when it was carried to the point of smoothing out all minor fluctuations, the time lag introduced between the application of the stress at the link and the complete response of the recorder was found to be twenty seconds. For horse work this corresponds to a distance of twenty yards or more, and the position marks impressed on the chart would refer, not to the part of the soil resistance trace immediately above them, but to a part some indefinite distance along the trace.

The details of the trace are also obscured if the record is condensed by using a slow chart speed, yet a reasonably condensed record is desirable for enlargement, since the field of the microscope then covers a good portion of the work. With a little experience a good compromise between these opposing requirements can be secured. In general a chart speed of about 1/4000 that of the implement gives good results. This is equivalent to one yard of chart for each two and a half miles travel of the implement. In horse ploughing this relation implies a chart speed of about 0·6 in. or 15 mm. per minute. With tractor or steam power implements, a faster chart speed is needed. For the dimensions of the copper tubing usually employed (length about 150 cm., internal diameter

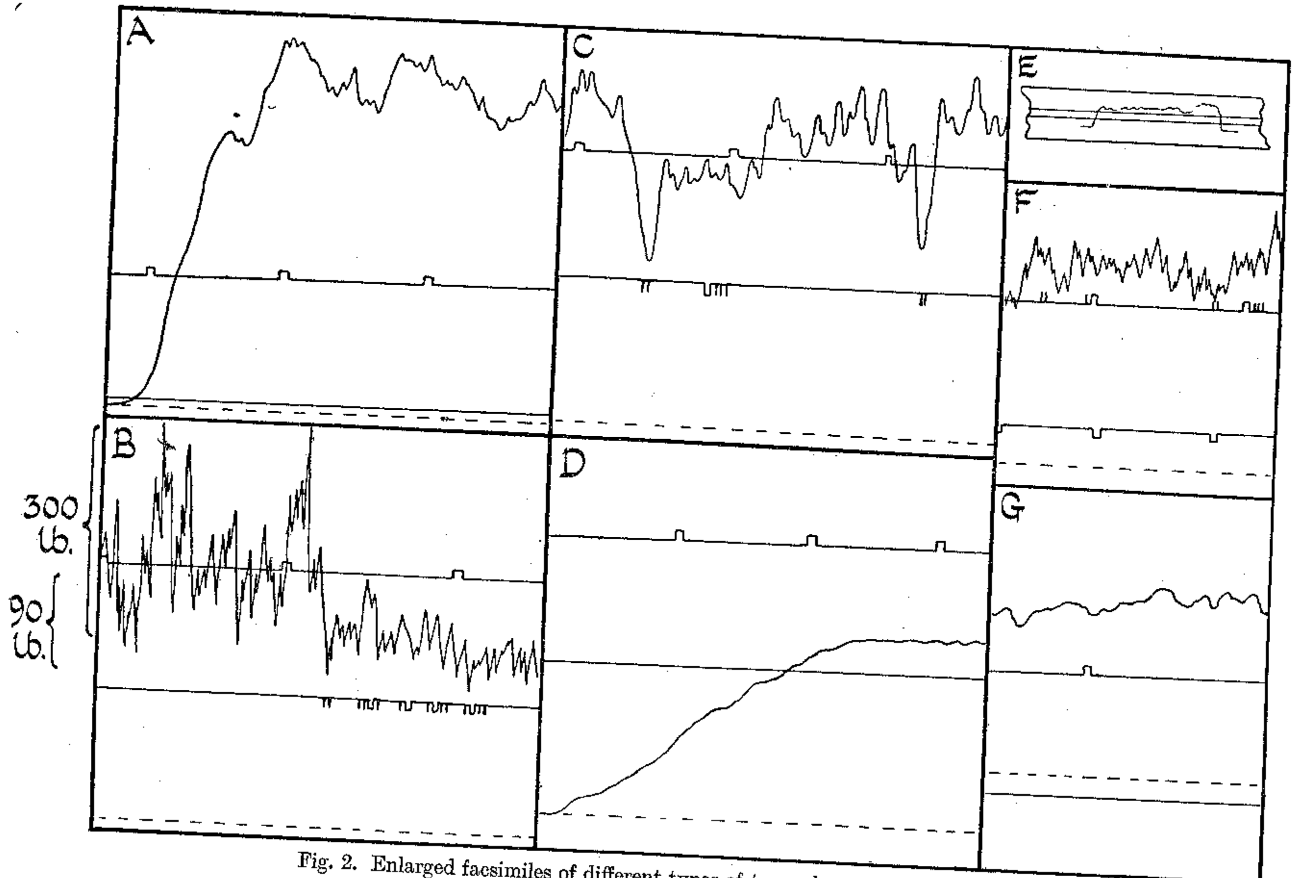


Fig. 2. Enlarged facsimiles of different types of trace: horse ploughing.

4 mm.), an ordinary engine lubricating oil is quite suitable for the pressure system in winter, but it is desirable to thicken it with gear oil in the warmer months.

The above remarks are illustrated by Fig. 2, showing different types of trace obtained with a horse plough. They are facsimile reproductions obtained with microscope and camera lucida as already described. As reproduced in Fig. 2 the magnification is about 10 diameters; a piece of the original trace is reproduced at *E* to the same scale, for comparison. In each of the enlarged traces the dotted line shows the position of the line of zero draught. The two straight full lines are the time and position scales.

The effect of damping is shown in a comparison of traces *A*, *B* and *D*, that refer respectively to normal, insufficient, and excessive damping. Trace *B* was obtained with thin oil and in warm weather; the record is characterised by many sharp changes in direction of the stylus movement, as it follows the abrupt changes in soil resistance. Trace *A* shows a normal amount of damping. The amplitude of the short period fluctuations is somewhat reduced and the sharp points are now somewhat rounded. A trace of this type is much easier to integrate with a planimeter than trace *B*, while the contribution to the total area of the areas within the sharp peaks is so small that their omission is unimportant. The time lag corresponding to trace *A* is not too large, as may be seen by the quick rise of the trace from the zero-draught line when the plough enters its work. Trace *D* shows excessive damping. The minor fluctuations have largely disappeared, and the trace takes about 20 sec. (two marks on the time scale) to rise to its full value.

The effect of the type of work itself on the character of the record is illustrated in traces *F*, *G*, *C* and *B*.

Trace *F* is a typical record on Rothamsted soil, a heavy loam with numerous flints, and shows the jerky "harsh" nature of the pull; trace *G* shows the much smoother pull characteristic of the Woburn sandy soil. Trace *C* is a record of work on Rothamsted soil with a ridging plough that was used in the early spring to break up old weathered furrows, containing much turf. It shows large fluctuations due to the uneven nature of the work, but the record is much more rounded than that in trace *F*. This is due to masses of turf acting as semi-plastic pads or buffers to the motion of the implement through the soil, and in consequence smoothing out the rapid fluctuations in pull. Trace *C* also demonstrates the use of the position marks for the indentification of particular portions of the record. Two such marks (each consisting of a double dot) are shown, specifying the beginning and end of plot *B*, that is indicated in the Morse code (–···). The position marks referred to the passage across the open furrows of the former ploughing; the drop in draught as the plough crosses these trenches is well shown, and the absence of any time lag is also demonstrated.

Trace *B* further illustrates the relation between the nature of the work and the type of record. The record falls obviously into two sections separated by the position mark (··), that represents the boundary between a stubble badly infested with couch grass (on the left), and a fallow, well cultivated portion (on the right). The latter is marked in Morse code with the first four letters of the word "fallow." On the stubble section the matted grass and clods of soil obstructed the plough, causing wide and erratic fluctuations in pull, covering a range of about 300 lb., which, by reference to the zero-draught line, is seen to represent over half the average value. On passing to the fallow portion, the implement travels normally, and the fluctuations at once settle down to the much smaller range of about 90 lb.

The Limitations of a Direct-reading Dynamometer.

The question whether the addition of a recording instrument could be avoided by taking the readings direct from the pressure-gauge attachment, can now be considered in the light of the above discussion.

It is evident, for the type of investigation dealt with in this series of papers, that it would be quite impossible to take accurate readings from a pointer that is rapidly fluctuating over half its total range, and even if this were possible the readings could not be taken down rapidly enough to secure a good mean for small-sized plots. Quite apart from this, the noting of position marks, speed of work, and other details would necessitate at least one extra observer and very practised and efficient co-operation if the results were to be reliable. Any method of damping the fluctuations sufficiently to make direct reading possible, quite spoils the coincidence between recorded draw bar pull and field position. There appears no escape from the conclusion that integrated records of a self-recording instrument are essential for reliable results, although for simple field demonstrations over a large area, a direct reading implement with heavy damping can usefully be employed.

Summary.

A new and improved type of dynamometer is described which by a simple interchange of parts can be used with the same percentage accuracy for all types of work from the lightest to the heaviest.

The instrument consists of (*a*) an hydraulic link weighing 16 lb. and placed in the hitch, (*b*) a recording mechanism weighing 15 lb. carried on any convenient part of the implement, and (*c*) a control box weighing 4 lb. carried by the operator. When packed in a stout box for transit and with all accessories the total weight is less than 100 lb. The instrument is of robust construction and has a minimum number of moving parts. Adjustments for stylus pressure, etc., are provided, but the necessity for using them hardly ever arises.

The instrument operates by recording the amount of movement in a Bourdon tube filled with oil and connected by narrow bore copper tubing to the oil in the hydraulic link.

The recording mechanism has been adapted from the Cambridge Instrument Company's Stress Recorder. The trace is impressed on a narrow, moving celluloid ribbon, and is permanent, and also unaffected by water, oil, or dirt. The optical properties of the trace give a clear and sharp magnified image, which can be traced by hand or photographed for purposes of integration. The construction of the instrument is such that the movement of the recording stylus is directly proportional to the stress applied to the hydraulic link.

In addition to this record of draught two other records, operated electromagnetically, are impressed on the ribbon: (*a*) a time trace showing a mark for each ten seconds, and (*b*) a position trace on which the passage from one plot to another is marked, and on which any field notes or other details are impressed in the Morse code by means of a tapping key carried by the operator. The styluses for these two records operate on the back of the ribbon so that the motion of the stylus recording the draught is unobstructed.

The method of magnifying the charts for integration with a planimeter is described, and typical records are reproduced, showing the character of the trace for different types of work, and the relation between the amount of detail on the trace and the degree of damping introduced into the oil system.

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