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Design and Development of a Torsiograph Having a Serrated-Condenser Pick-up Unit

By

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Summary.—Reasons for Enquiry.—The instrument that forms the subject for this report has a condenser pick-up unit to which a carrier wave is applied: it measures, directly, instantaneous angular displacements due to shaft twist. The pick-up originated in a surface-strain gauge (embodying serrated-condenser elements) which had been the subject of some preliminary experimental work.

Range of Investigation.—Two main types of torsiograph are contrasted in relation to their application and the present torsiograph is described. Results of calibration tests with different serrations and air-gaps are given, together with a general account of experience gained during a total of some 10 hours running with the instrument fitted to a Merlin II engine. Some typical records are included but not the results of the torsional vibration investigation—which will form the subject of a separate report. Calibration results are given from which the serrations appropriate to particular applications can be decided.

Conclusions.—The torsiograph gives very satisfactory results when due care is taken with electronic equipment.

The natural frequency of the instrument is such that torsional vibrations having a frequency as high as 80,000 cycles per minute can be recorded with ease.

The instrument provides a means of making continuous observations of torsional vibration at a moderately remote station and it can be adapted for making observations in flight.

1.0. *Introduction.*—When considering a shafting system undergoing torsional vibration, it is usually more important to know the maximum range of stress-fluctuation than to have a measure of the maximum irregularity of rotation in the system. Range of stress-fluctuation can be determined more directly and more accurately from measured fluctuation of twist (over a selected length of practically massless shafting) than from measured irregularity of rotation at a selected point in the system: to infer stress-fluctuations from measured irregularity involves having a knowledge of the equivalent dynamic system and such knowledge may be by no means precise—particularly where matters are complicated by the presence of pendulum vibration absorbers. Thus it is usually more satisfactory to use an instrument that measures twist-fluctuation than one that measures irregularity of rotation. The Royal Aircraft Establishment optical torsiograph[1] is primarily of the former type and so also is the instrument that forms the subject of this report: both can be converted into the latter type by securing one member of the metering element to a floating flywheel suitably mounted.

Instruments of the former type can be applied more easily to fixed-pitch propellers than to those having pitch-changing mechanism: for the latter propellers, it is usually necessary to fix the pitch. Although the directness of the measurements given by the R.A.E. optical torsiograph is a powerful point in its favour, it has been expected that this instrument would yield place eventually to electrical instruments: the change is now in process of accomplishment with the use of alternative types of pick-up units.

R.A.E. Report E. 3934.

Electrical pick-up units can be arranged to give twist-oscillation signals from locations in the shafting to which access is impracticable for optical recording. This factor is particularly important in relation to counter-rotating propellers as the successful development of these propellers is not to be anticipated without having recourse to torsiograph observations, and the application of the optical torsiograph for the purpose is distinctly limited. In some instances, as with the Merlin engine, electrical recording renders it possible for torsional vibration observations and strain-gauge observations on the propeller blades to be made simultaneously so that the study of their inter-relationships may be facilitated : also, in some aircraft, electrical observations of torsional vibration can be made in flight.

It happens that the Merlin engine is well suited to the fitting of an electrical pick-up unit provided this can be housed in the shaft which transmits the drive from the crankshaft to the reduction-gear pinion. Then the pick-up can be inserted through the opening in the front of the gear housing normally covered by the constant-speed propeller control unit and this unit can be replaced by the slip-ring unit required for making electrical connections. Accordingly, the development of the instrument described in this report has been carried out in relation to the Merlin engine. From the basic information obtained, pick-up units of widely varying size and shape can be designed to suit other applications : in some instances it may be expedient to arrange the pick-up unit to surround a shaft instead of to go inside it.

An important part of the instrument as a whole is the provision for making a satisfactory earthing connection and for conveying the vibration signal away from the rotating shaft with due regard to electrical screening : this has entailed more development work than the pick-up unit itself which has given practically no trouble.

The type of instrument is such that calibration can be effected statically : also, the vibration signal is superimposed on a signal of mean-torque. So far, attention has been directed mainly to the vibration signal and thus the mean torque has been observed only in a very general way. A capacity type " slip-ring " has been tried but gave trouble owing to cracking and flaking of the insulating material. Micalex had been adopted for the insulation to meet the temperature conditions and this substance proved not to be strong enough in this application owing to the existence of sudden changes of section. A unit of revised and simpler design has now been made for trial. It is desirable to use a capacity-type " slip-ring " for torsiograph work, but not essential, as it is not necessary to eliminate all drifting of the zero datum.

2.0. *Description of the Torsiograph Apparatus.*—The apparatus comprises :—

(i) A pick-up unit adapted to be fitted into a hollow shaft in the torsional system, or else to fit around a shaft, and containing a condenser of such design that its capacity varies linearly with shaft twist.

(ii) Means for transmitting the pick-up signal from the rotating shaft to an adjacent stationary point : also, means for earthing the shaft.

(iii) Electronic apparatus in which the signal is amplified for transmission to an oscillograph.

(iv) A special low-capacity lead for connecting the pick-up unit to the electronic apparatus at a fairly remote place.

(v) An oscillograph, including means for obtaining permanent records with timing signals on them.

(vi) Means for calibrating the instrument.

So far, the apparatus has been used only as adapted to one engine, namely, the Merlin, and the detailed description which follows relates to this particular application. From a study of this application and of the results obtained in the course of its development the adaptation appropriate to other applications will become apparent.

2.1. *Serrated-Condenser Torsional Pick-Up Unit.*—Referring to Fig. 1, the pick-up unit is shown fitted in the bore of the pinion driving shaft of a Merlin engine: the bore is 1·5625 inches. Tubular member A is of mild steel and has fine longitudinal internal serrations in the region of the smaller bore. These serrations are formed by cutting rectangular slots—using a small slotting machine having an accurate indexing arrangement. The inner tubular member B is also of mild steel and has corresponding external serrations—formed by using a milling cutter. (*See* Fig. 2.)

Member B is secured to the central hollow shaft C through the medium of the insulating member D and connected electrically to the screened signal lead shown.

Between A and B there is a fine gap which is maintained by the ball bearings (which are pre-loaded) and these members constitute a condenser, the capacity of which changes with relative angular displacement of the members. (*See* Fig. 2.) Member A in Fig. 1 is registered to the angular position of station PP in the pinion driving shaft by the expanding grip shown and member B is registered similarly to station QQ*. Under the full mean-torque of the Merlin II engine, the twist of the shaft between PP and QQ is represented by a circumferential displacement of approximately 0·0025 inch at the condenser gap and it will be understood that the sensitivity of the apparatus required to be such that the change of capacity caused by displacements of this order of magnitude shall give a fairly large deflection in the oscillograph record: this presents no difficulty, as will be shown by quantitative examination of the matter. (*See* para. 3.)

It is clearly very desirable that the sensitivity shall be constant over the full range of movement due to shaft twist at the most pronounced critical—that is to say, the capacity-displacement relationship should be linear over this range. It has been found that this condition can be met by designing the serrations suitably. In this connection it should be noted that whereas with a variable-gap condenser excessive movement will cause contact of condenser elements (or of corresponding stops), combined with difficulty in getting linearity over the requisite range, the condenser under discussion is not limited mechanically as regards allowable movement and thus it requires no stops. The pick-up unit is normally fitted so that inner and outer teeth half overlap when the shaft is transmitting about full mean-torque: this gives the fullest range of linearity on either side of such torque.

Rubber sealing rings R are shown which prevent the ingress of oil vapour to the condenser, so that the gap remains filled with the dry air present under the conditions chosen for assembly—with the pinion driving shaft out of the engine and in a dry place.

The drive for the slip-ring and the earthing connection is taken from an adaptor E securely attached to the crankshaft pinion. The slip-ring unit is attached in place of the constant-speed propeller control unit and the electrical connections M and N are made by low capacity sockets. (M.A.P. Specification reference 10H/183 and 10H/10330). The plug of socket M on the driving adaptor is connected to the screened lead from the inner condenser cylinder B by sweating a wire to the centre of the socket on assembly. In order to exclude oil, a rubber ring is placed between the adaptor for driving the slip-rings and the pinion driving shaft: the other end of the torsiograph is plugged with a rubber stopper and sealed with plastic rubber.

2.2. *Slip-Rings and Earthing Connections.*—For transferring the vibration signal, a phosphor bronze ring F of 1·25 inches diameter with a 90 deg. groove, is used in conjunction with the copper flex-wire brush G which is held against the ring by a flexible holder made of phosphor bronze and of such form as to give universal flexibility.

The instrument could not be earthed satisfactorily by connection to the engine body because variations of resistance and capacity at the oil films between rotating and stationary parts produce the effect of spurious signals. Furthermore, the earthed parts of the pick-up unit itself requires to be interconnected suitably as indicated in Fig. 1.

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* An alternative design of grip, which takes less axial room, has been tried with success on another pick-up unit. The gripping action is obtained by bolting together a pair of Belville washers.

The earth connection is made by means of the Nichrome wire J which is shaped to a needle point and secured in the end of the shaft. The point just perforates a leather diaphragm K which seals some mercury L in a small container having three mounting screws for adjustment. This arrangement combines true running of the needle with minimum relative velocity of needle and mercury, These refinements in making the connections are the outcome of experimental development and have proved to be satisfactory: during a running time exceeding two hours no " mush " appeared on the cathode ray tube screen and the brushes did not require attention. The mean value of the torque could not be obtained because there was a drift of low indeterminate frequency caused by changes in the capacity and inductance of the brushes associated with curvature and variation of resistance at the brush contacts.

2.3. *Electronic Tuning Circuit.*—The electronic circuit used was made by Messrs. Southern Instruments Ltd. The circuit supplies a carrier wave of one megacycle frequency to the condenser in the pick-up unit. This condenser is part of a tuning circuit which also contains an inductance, screened lead, tuning condensers and calibrating condenser. The carrier wave is filtered from the output and there are no condensers in series with the output: thus D.C. amplifiers may be used. The maximum sum of the capacities of element and leads is 600 $\mu\mu$F. The response of the circuit is a linear output of approximately $\pm$ 2volts for a change in capacity of ± 10 $\mu\mu$F.

2.4. *Insulating Materials and Leads.*—To obtain the required high sensitivity it is necessary to use a high carrier frequency and, in consequence, dielectrics are required that have a low power-factor at this frequency. Such dielectrics comprise mica, ebonite, mycalex and the synthetic insulators: polystrene distrene,, ethene, etc. Mycalex was chosen for the insulator D because of its good dielectric properties, its ability to withstand heat with no loss of mechanical strength and the constancy of its dielectric properties with temperature change. To eliminate wear during assembly of this insulator on shaft C, a thin steel bush was inserted in the bore: in one instance, radial cracks appeared in the mycalex after assembly but this did not affect the functioning of the bush. Bakelised fabric gave trouble owing to its high power factor and paper proved troublesome in damp atmosphere. Changes in the capacity to earth outside the strain element are recorded as strains and, as the signal is produced by changes of capacity less than 20 $\mu\mu$F. out of a total of 600 $\mu\mu$F. special care must be taken with all leads. They must be insulated with a good quality dielectric having an earthed screen outside the insulation. The smaller the capacity per unit length of lead between conductor and screening the longer is the lead that may be used between the strain element and the recording apparatus.

There are several special low-capacity cable-leads which fulfill the condition that the central wire shall remain at an almost invariable distance from the earthed screen in spite of a reasonable amount of flexing. In an instance where severe vibratory movement of cable proved troublesome the difficulty was overcome by installing a short length of standard M.A.P. " Uniflexmet " cable. Only short lengths of this cable can be used because it has a relatively high capacity per unit length: it has adequate flexibility and at the same time the radial stiffness is such as to prevent the capacity from changing appreciably.

For some applications leads may be built up on a metal surface using plastic dielectrics, in which case the earthed screen may be obtained by using a conducting paint such as "Aquadag."

Change in temperature alters the capacity of all the above leads and if the temperature is changing a drift in the steady value of the strain will result. This change is too slow to affect the usual alternating readings. If necessary, this drift can be avoided by using a fine wire stretched taut along the centre of an earthed tube with insulator supports at intervals: the wire may be tuned by tension and spacing of supports to have a frequency outside the range of important vibration frequencies of the adjacent structure.

2.5. *Recording Apparatus Employed.*—The output from the tuning circuit is magnified by D.C. amplifiers and led to a cathode ray tube. The spot on the cathode ray tube is photographed on 59 mm. wide paper. Typical records are shown in Fig. 3. The timing signals on the film are obtained by the two crystal oscilloscopes, one actuated by engine contacts and the other by a 50-cycle tuning fork.

2.6. *Means of Calibration.*—A calibrating rig is used in which relative angular movement of the gripping points of the condenser unit is recorded by means of an arm bearing on a dial indicator. Corresponding capacity changes are obtained from the calibrating condenser in the tuning circuit using the D.C. amplifiers. As the ratio of the radius of the dial indicator to the radius of the serrated-condenser gap is known, change of dial reading can be expressed as movement at the gap. Some calibration curves are given in Figs. 4–7 : they are commented upon in para. 3.

3.0. *Serrated-Condenser : Design and Experiment.*—The torsional unit originated in a variable-condenser pick-up unit in which a slide having fine transverse serrations moved parallel to corresponding serrations in the surrounding member. After a certain amount of development work had been done on the strain-gauge, it became evident that basic data for the design of serrated condensers having fine serrations and air-gaps could be obtained with greater facility by making observations of capacity change on *cylindrical* elements (with various air-gaps and longitudinal groovings) than on *flat* elements—because it is easier to obtain true surfaces and known air-gaps with the former type.

As there was need for an improved torsiograph pick-up unit, the cylindrical pick-up was designed for signalling instantaneous twist in a length of shafting ; it was arranged to fit into the pinion-driving shaft of the Merlin engine because this afforded a ready means not only of developing the torsiograph but also of exploring the possibility of the pick-up being developed further for use as a transmission dynamometer.

The condenser gap was made small at first and then increased in stages by grinding after observations of capacity-change with displacement had been made in the calibrating circuit.

3.1. *Theory.*—The capacity of a long plain annular condenser is proportional to the dielectric constant, the area and the logarithm of the ratio of outer to inner radius, but the radial gap is such a small fraction of the gap radius for the condensers concerned here that it suffices to ignore the fact that the condenser surfaces are curved—that is, to work from the simple plate condenser formula. By introducing an empirical co-efficient " η " to take account of distortions of the electrostatic field associated with serrations, we have :—

$$(\text{Capacity of serrated condenser in } \mu\mu\text{F.}) = \frac{\eta\, k\, A}{3{\cdot}6\, \pi\, t}$$

where k = dielectric constant (unity for air).

A = overlap area of the elements in sq. cms.

t = gap between elements at overlap in cms. (*i.e.*, radial gap).

η = a coefficient which is unity when the gap is extremely small and which decreases as the gap increases.

If the charge distributed itself uniformly, the change of capacity with relative position of the teeth would be linear, but, as the charge distribution cannot in fact be uniform, the actual sensitivity and range of linearity remained to be determined by experiment.

3.2. *Results with* 180 *Tooth-Elements.*—The calibrations given in Fig. 4 were obtained with an element of 1·26-inch diameter having 180 tooth-elements, 0·008 inch wide, and slots 0·0135 inch wide by 0·010 inch deep. The radial gap corresponded to a diametral clearance of 0·0015 inch*. It will be seen that the sensitivity is 28 μμF. per 0·001 inch of movement at condenser face, and that the range of linear response is 0·006 inch.

In order to find the effect of width of gap on the sensitivity, the diametral clearance was increased progressively to 0·003 inch, 0·004 inch and 0·005 inch ; the calibration curves are given in Figs. 5 and 6. The calibration curves repeated at different relative angular positions of the cylinders and the sensitivities were the same for increase and decrease in capacity.

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*Reference will be made throughout to diametral clearance because this value is known accurately whereas the gap on the radius may not be exactly half the above value, due to very slight error in concentricity.

The values of the sensitivities obtained from the calibration and by calculation using the formula of para. 3.1 are given in Table 1 and plotted in Fig. 8.

The percentage of actual sensitivity to calculated sensitivity is given in column 10 of Table 1 and plotted in Fig. 8; range of linearity of response is given in column 11 of Table 1. The range is only slightly affected by change of gap but the ratio of actual to calculated sensitivities decreases with the increase of gap. This shows that for gaps of the order tried a condenser element formed by two teeth and adjacent gaps cannot be considered to have the properties of a condenser with infinite area in the central region of the overlap associated with distortion at each side due to the termination of the plates. This would result in the agreement of actual and calculated sensitivities and in the reduction of range of linearity with increase in gap: hence the effect of the small breadth of each condenser element on the field of the condenser is to distort the whole of the lines of force in the field. This distortion increases with width of gap. The range of linear response is only slightly reduced with increase of gap.

3.3. *Results with 90 and 60 Tooth-Elements.*—Two sets of values for different condenser elements of 90 and 60 teeth have been included in Table 1. There are readings for elements with 0·003 inch diametral clearance for 180 and 90 teeth respectively. The ratios of actual to calculated sensitivities are 48% and 56% for corresponding ratios of tooth width to mean radial gap of 5·53 and 12·65. This indicates that, although ratio of tooth width to gap has an effect, the most important factor in the design is the radial gap.

The last set of values in Table 1 is for an element of 60 teeth and a gap of 0·006 inch. This shows that the ratio of actual to calculated sensitivities is tending to become constant with increase of gap at a value of about 30%.

The maximum gap to be used for the pick-up unit is about 0·006 inch.; any larger gap results in an unnecessarily large pick-up unit.

The element selected for the tests on a Merlin engine was the one with 90 teeth and 0·003 inch diametral clearance, because of its large range of linearity, combined with adequate sensitivity. Full mean-torque of the engine corresponds to 0·0025 inch movement at the condenser face. The large range facilitates correct setting of the pick-up unit when assembling it in the pinion driving shaft.

3.4. *Running Experience with the Torsiograph.*—Obesrvations were made on a Merlin II engine over a range of engine speeds and with different blade pitch settings. The electronic apparatus was housed in a test cubicle so located as to require about 25 feet total length of cable lead. Repeat observations gave consistent results; at one time, the instrument was removed from the engine, stripped, re-assembled and replaced three times and the same torsiograph results were obtained. (The analysis of the observations made will form the subject of a separate report.)

The instrument was designed to have a very high natural frequency and the tests confirmed that this is well beyond the range of usual forcing frequencies. It was found that vibrations of frequency as high as 80,000 cycles per minute (twice per reduction tooth engagement) can be recorded with ease.

Low amplitude vibrations of higher frequency than this were recorded but it was not established that these were genuine; they may have been due to microphony of the electronic recording apparatus.

Before the matter was put to trial, it was considered that the pre-loaded ball bearings in the pick-up unit might wear and develop slackness and, to obviate this possibility, there was fitted in the space provided for each of the two ball bearings a steel wheel-like member, machined from the solid, having six thin spokes designed to accommodate the amount of rotation to be experienced. There were attendant assembly difficulties, however, which resulted in damage to the spokes and, in consequence, the pre-loaded ball bearings (which had already been used for some calibration tests) were fitted for the engine tests. No trouble was experienced with these during the tests—which involved a total of some 10 hours running. However, for some purposes it may be desirable to use spider supports although they require special care in handling.

To obtain satisfactory results it is essential that due care be taken with the electronic system. Leads must be fully screened and properly earthed, and the conductor must be maintained at a constant distance from the screening. The dielectrics used must have a low power-factor at the carrier frequency (one megacycle) and, as damp atmosphere affects the tuning circuit and dielectrics, the peak value of the output current of the tuning circuit must be checked at each run. In this connection, it is well to house as much as possible of the apparatus in a warm and dry place. The cathode ray tube requires to be in good working condition and focus.

A moving film camera, having a lens of 2 inches focal length having $f=1\cdot7$, was used in conjunction with a blue vacuum cathode ray tube with 600 volts on the anode. Records were taken on Kodak 59 mm. recording papers RP 25 and RP 30, with satisfactory results. Good results were obtained also using a blue gas-filled cathode ray tube at about 900 volts in conjunction with a lens of 3 inches focal length, having $f=1\cdot7$, and 35 mm. panchromatic film.

The slip-rings were not found to require frequent cleaning. From other experience it is considered that silver rings and silver-morganite brushes would serve as well provided the brush holders be earthed through a suitable spring connection.

The mercury earth connection worked well when set so that the needle projected about one millimetre into the mercury.

4.0. *Conclusions.*—The torsiograph gives very satisfactory results when due care is taken with electronic equipment. (*See* para. 3.4.)

The natural frequency of the instrument is such that torsional vibrations having a frequency as high as 80,000 cycles per minute can be recorded with ease.

The instrument provides a means of making continuous observations of torsional vibration at a moderately remote station and it can be adapted for making observations in flight.

REFERENCE

Ref. *No.*	*Author.*	*Title.*
1	The Staff of the Engine Experimental Department, R.A.E.	The R.A.E., Mark Va, Torsiograph, R. & M. No. 1762, May, 1936.

TABLE I

R.A.E. Serrated Condenser Torsiograph. Details of Serrations and Sensitivities.

No. of teeth	Length of teeth ins.	Diametral clearance ins.	Width of slot ins.	Depth of slot in inner element ins.	Width of tooth ins.	Width of tooth	Sensitivity μμF. per ·001 movement at condenser face			Range of linearity. Movement at condenser face
						(mean gap on radius)	Actual	Calculated	$\frac{\text{Actual}}{\text{Calculated}}$ %	
180	0·75	0·0015	·0135	0·010	0·008	10·65	28·05	37·57	74·6	0·006
180	0·75	0·003	·0135	0·00925	0·008	5·33	8·75	18	48·6	0·0055
180	0·75	0·004	·0135	0·00875	0·008	4	4·85	12·62	38·4	0·0055
180	0·75	0·005	·0135	0·00825	0·008	3·2	3·65	9·8	37·3	0·005
90	0·75	0·003	·025	0·030	0·019	12·65	5·4	9·61	56·2	0·014
60	1·57	0·006	·035	0·030	0·031	10·33	5·5	15·8	34·8	too large to calibrate

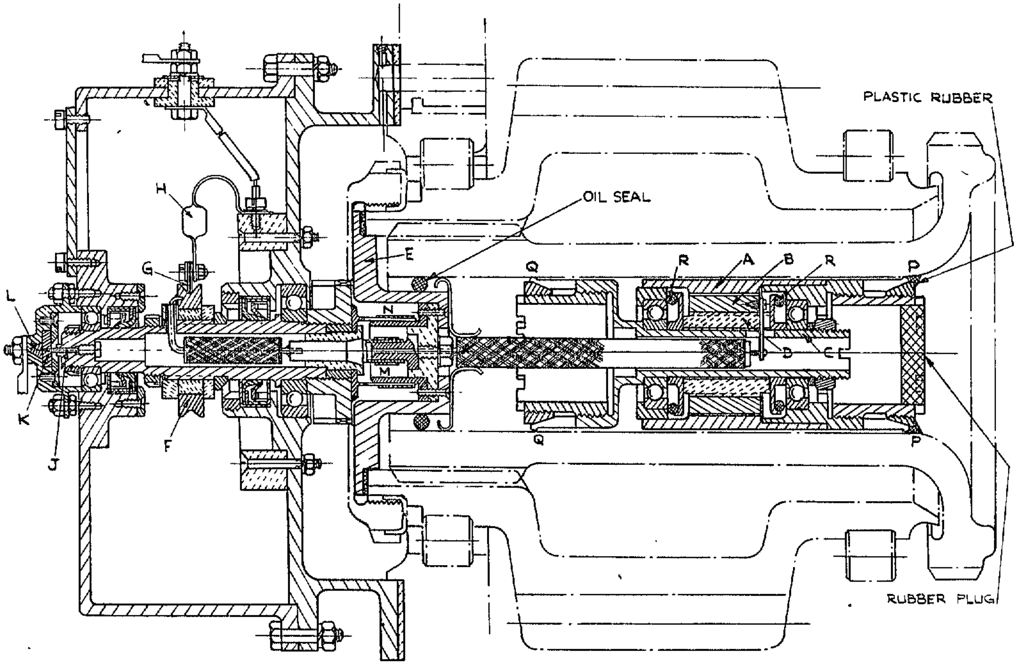
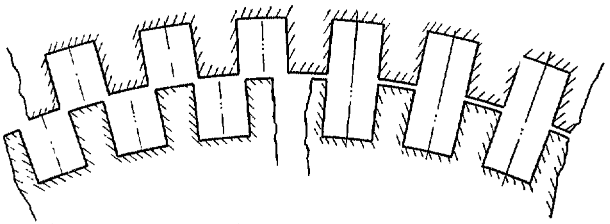
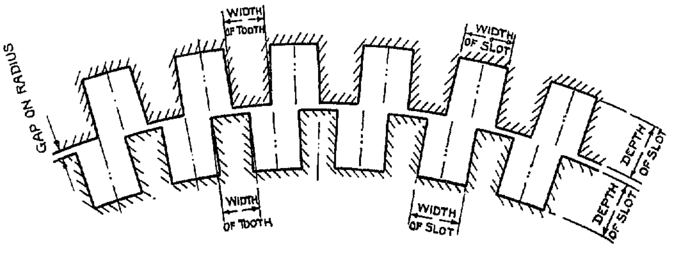


FIG. 1—Assembly of capacity type twist pick-up in "Merlin" engine.



POSITION OF TEETH FOR MINIMUM VALUE OF CAPACITY.

POSITION OF TEETH FOR MAXIMUM VALUE OF CAPACITY



APPROXIMATE POSITION OF TEETH FOR VALUE OF CAPACITY GIVEN AT CENTRE OF LINEAR PORTION OF CALIBRATION CURVE.

FIG. 2—Enlarged view of serrations of R.A.E. condenser torsiograph.

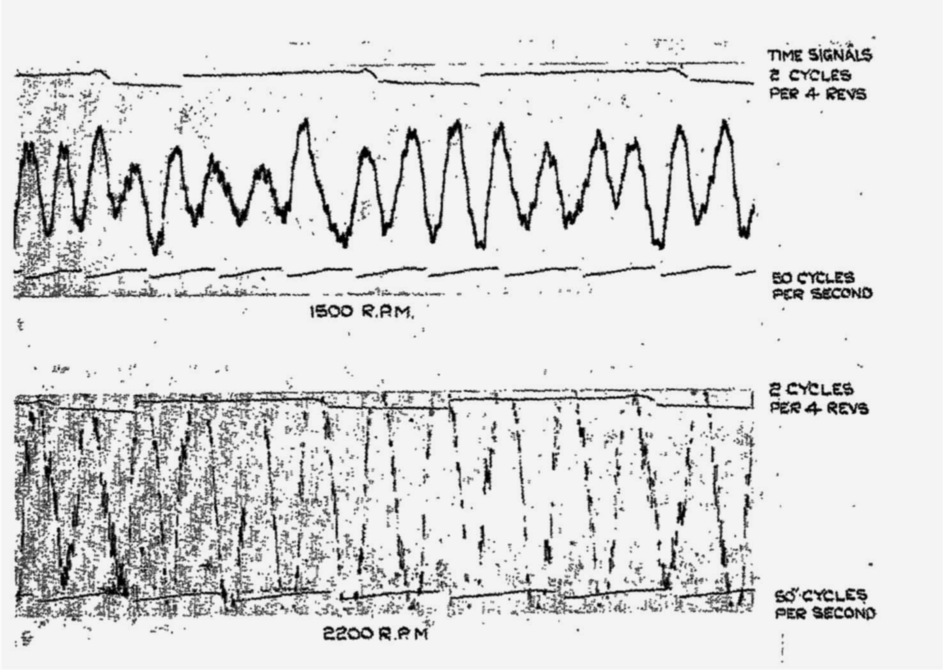
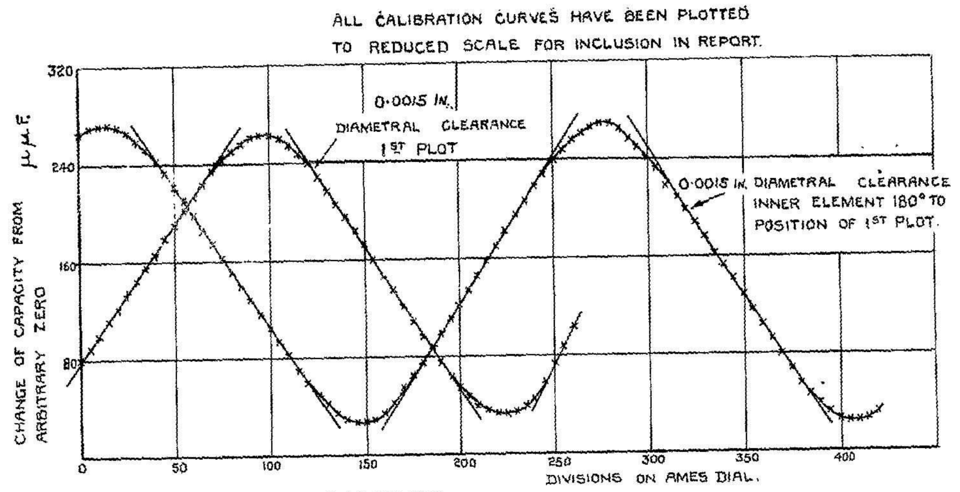


FIG. 3—Records of R.A.E. serrated capacity type torsiograph taken on Merlin II blade angle 22·5° at 42in. station.



12·2 CLOCK DIVISIONS = 0·001 IN MOVEMENT AT CONDENSER FACE

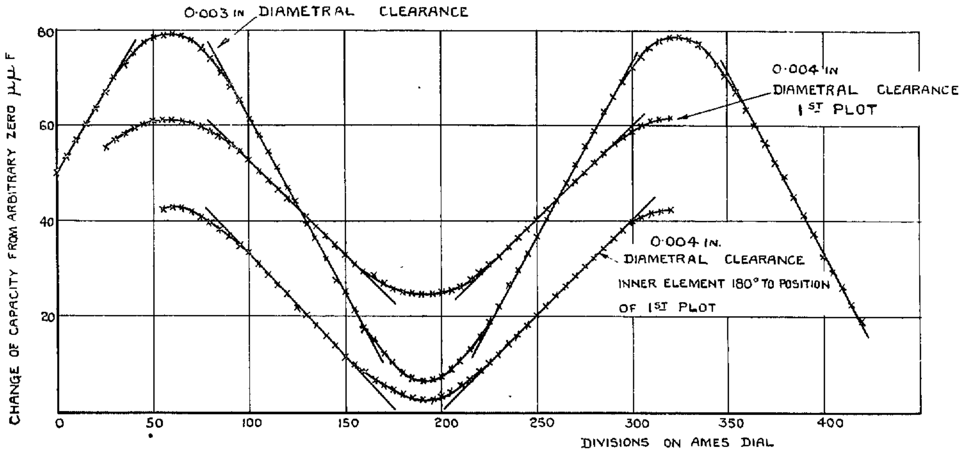
180 TEETH 0·008 WIDE. SLOT 0·0135 IN WIDE.

SLOT 0·010 IN DEEP FOR 0·0015 IN GAP.

DIAMETRAL CLEARANCE 0·0015 IN LINEAR RANGE 0·006 IN.

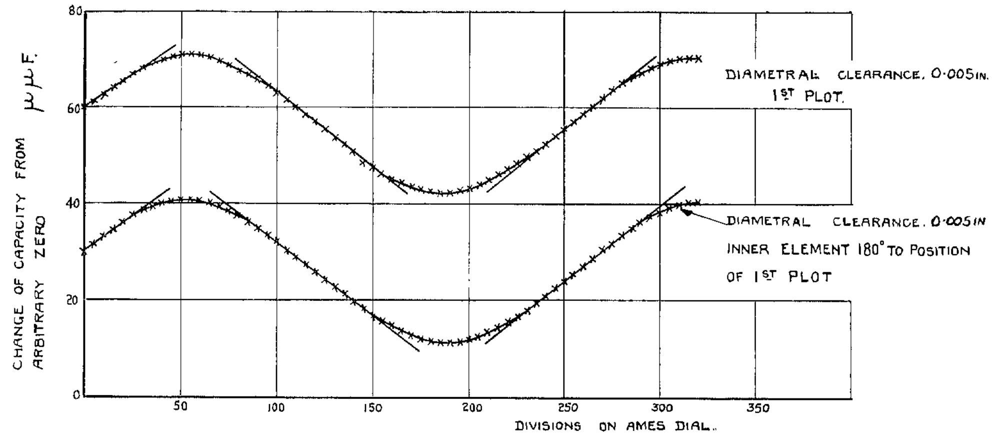
SENSITIVITY 28 μμF PER 0·001 IN MOVEMENT AT CONDENSER FACE.

FIG. 4—Calibration of torsiograph pick-up unit.



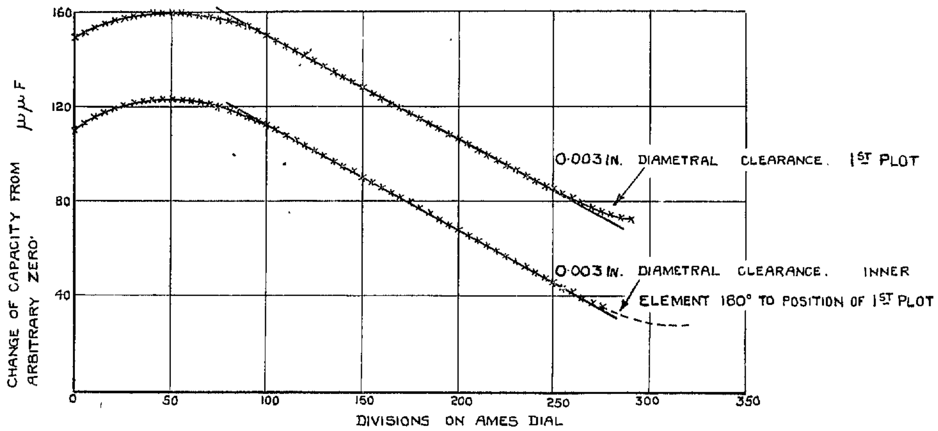
12 2 CLOCK DIVISIONS = 0·001 IN MOVEMENT AT CONDENSER FACE.
180 TEETH 0·008 IN. WIDE
SLOT 0·0135 IN WIDE 0·010 IN DEEP FOR 0·0015 IN GAP
DIAMETRAL CLEARANCE 0·003 IN: RANGE 0·0055 IN.
SENSITIVITY 8·75 μμF PER 0·001 IN MOVEMENT AT CONDENSER FACE
DIAMETRAL CLEARANCE 0·004 IN: RANGE 0·0055 IN.
SENSITIVITY 4·85 μμF PER 0·001 IN. MOVEMENT AT CONDENSER FACE.

FIG. 5—Calibration of torsiograph pick-up unit.



12·2 CLOCK DIVISIONS = 0·001 IN. MOVEMENT AT CONDENSER FACE.
180 TEETH 0·008 IN WIDE: SLOT 0·0135 IN WIDE 0·010 DEEP FOR 0·0015 GAP
DIAMETRAL CLEARANCE 0·005 IN. RANGE 0·005 IN.
SENSITIVITY 3·65 μμF PER 0·001 IN MOVEMENT AT CONDENSER FACE

FIG. 6—Calibration of torsiograph pick-up unit.



12·2 CLOCK DIVISIONS = 0·001 IN MOVEMENT AT CONDENSER FACE

90 TEETH 0·019 IN WIDE. SLOT 0·025 IN WIDE. 0·030 IN DEEP FOR 0·003 IN GAP.

DIAMETRAL CLEARANCE 0·003 IN. RANGE 0·014 IN.

SENSITIVITY 5·4 μμF PER 0·001 IN MOVEMENT AT CONDENSER FACE.

FIG. 7—Calibration of torsiograph pick-up unit.

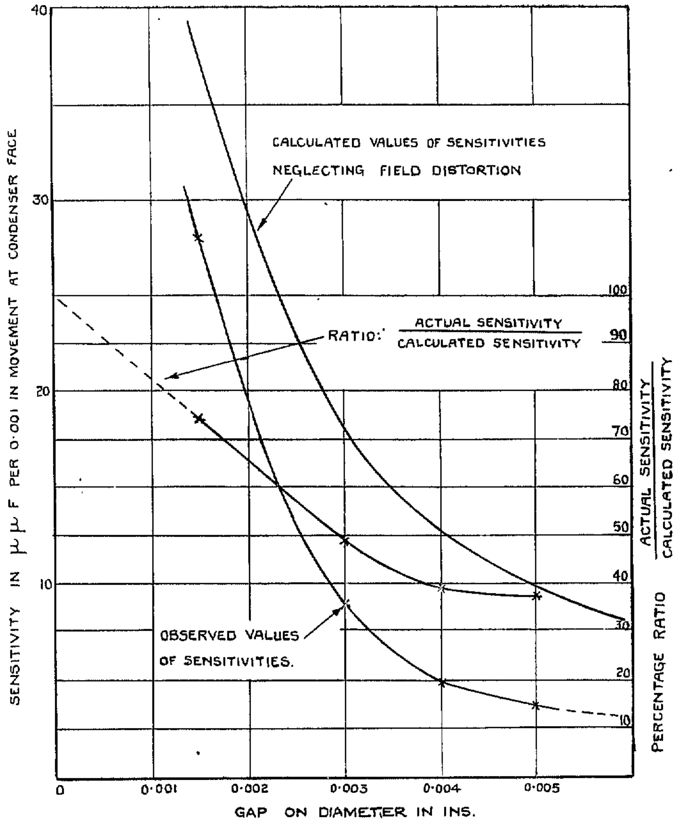


FIG. 8—Sensitivity of torsiograph pick-up unit for various gaps.

(71707) Wt. 9/7116 12/45 Hw. G. 377/1

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