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ROYAL AIRCRAFT ESTABLISHMENT

FARNBOROUGH, HANTS

TECHNICAL NOTE No: I.A.P.1028

INTERIM NOTE ON THE DEVELOPMENT OF A MAGNETIC POWDER CLUTCH

by

F.L.WEST, A.M.I.Mech.E.

UNCLASSIFIED

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Interim Note on the Development of a Magnetic Powder Clutch

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R.A.E. Ref: IAP/1500

SUMMARY

The most important test results obtained during the course of work on experimental magnetic powder clutches and iron powder materials in IAP Dept., RAE have been collected to illustrate difficulties being encountered with magnetic media for the guidance of future workers.

The Note covers an investigation of shear forces transmitted to a flat steel plate by magnetised iron powder media, and outlines phenomena observed during tests on experimental clutches of disc and cylinder rotor construction. The development and performance of a small cylinder clutch designed for use with an aircraft autopilot servo-actuator is dealt with in some detail up to the stage of small quantity reproduction.

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1 Introduction

Although the general properties of magnetic fluid and powder clutches are now becoming well known, empirical methods continue to be employed for the purpose of design and development. This is because our understanding of the behaviour of the magnetic medium in relation to the clutching process is incomplete.

Before the device can be exploited to its fullest advantage, it is considered that this process should be clearly understood.

With this purpose in mind, the most important test results obtained during the course of work on experimental clutches and iron powder materials in IAP Dept., RAE have been collected in this note for the guidance of future workers. Only those observations considered to have a direct bearing on the clutching action have been recorded, other problems are treated as incidental.

Further experiments to clarify certain points are still in hand.

2 Scope of the Work

An experimental examination of the performance of the clutch was started at RAE during 1948 to assess its suitability for application to a servo actuator for use with the RAE Type B autopilot. More recently an actuator incorporating these clutches has been developed to meet this requirement. The tests can be separated into three main groups:-

(a) an investigation of the system to establish data on which to base a design;

(b) an examination of the performance of clutches constructed from the results of this data;

(c) engineering development of the clutches to fulfil a specification.

3 Preliminary Investigations

As an introduction to the work it was apparent that some preliminary experiment was necessary to relate torque transmission with physical dimensions of the clutch. A simple test apparatus was conceived for the purpose whereby the force transmitted by a magnetic system of this nature per unit surface area could be measured. This apparatus is shown in Fig.1. It consisted of a flat rectangular plate made of soft steel and located by guides formed in opposite walls of a closed brass container. Movement of the plate was thus permitted only in a lengthwise sliding manner through the container. This sub-assembly was positioned between the poles of an electromagnet with the plane surfaces of the plate parallel to the pole face, and dimensions were chosen such that the pole area was slightly greater than that part of the plate surface enclosed by the container to ensure a uniform magnetic flux distribution across the section. Dimensions of the enclosed plate were carefully noted.

3.1 The experimental procedure was to fill the container with a sample of iron powder material through a filler cap provided, thereby immersing a known plate area.

On energising the electromagnet, in accordance with the principle of the clutch, the force transmitted by the powder to the plate, parallel to its surface, could be measured by observing the force necessary to slide the plate slowly through the container.

3.2 Although not strictly representative of the dynamic working conditions present in a clutch, this apparatus provided some valuable design information and appeared to be a particularly useful means of comparing the quality of different types of magnetic medium. A number of iron powder samples had been obtained from various sources and each in turn was subjected to test in the above manner. By varying the electromagnet excitation in progressive stages a series of characteristics, one for each sample, relating slip force and excitation were obtained.

3.3 The pole flux density corresponding to a given excitation in ampere-turns was now determined by further experiment, and since the working surface area of the plate was known, it became possible to plot these characteristics to more convenient ordinates of force per unit area and flux density. The results are given in Fig.2 from which a remarkably wide difference in performance of the various materials will be observed.

3.4 As a means of achieving minimum dimensions for a clutch designed to fulfil a given torque output requirement, clearly it is necessary to employ a medium producing a high ratio of slip force to excitation. The slope of the characteristics given in Fig.2 is therefore an important measure of quality. Judged on this basis, electrolytic iron powder appeared to be the most promising material but it was evident from the manner in which slope of the characteristic steadily increased with excitation that a change in working conditions was occurring.

On investigating this effect more fully, it proved to be caused by impression of iron particles into the plate surface which, in a clutch, may cause rough transmission and would probably encourage rapid wear. These possibilities were not confirmed during the later test running on experimental clutches, but at this stage of the work, electrolytic iron was considered less suitable than sample C of Fig.2 which showed a more linear characteristic of slightly lower but comparable slope.

3.5 It is interesting to note here the coarser particle size and superior performance of both these powders relative to the other samples tested.

3.6 Having selected a suitable iron powder, a second series of measurements were made to determine the effects of adding oil. From Fig.3 it will be observed that even small addition of oil caused a marked reduction of transmitted force and, as far as could be judged, this loss was not accompanied by an improvement in smoothness of motion.

3.7 As a general conclusion from these tests it was evidently desirable to carefully consider using dry iron powder as the magnetic medium even at the expense of a slight loss of smoothness. This would not only permit an economy in size and weight but would also simplify the problem of sealing a clutch and obviate any difficulties arising from sludging of fluid mixtures.

4 General Considerations

Having derived primary data on which to base the design, it was now proposed to construct an experimental clutch. For the application in mind, a power transmission of 30 to 40 watts would be required, preferably using a clutch of small dimensions running at high speed.

4.1 A disc type rotor construction was chosen for the first attempt since it appeared to be simpler than the alternative cylinder version. It was realised that centrifugal effects on the iron powder would limit the speed at which the clutch could be used, but no great importance was attached to the point at this stage.

5 Tests on the Disc-Rotor Clutch

The form of magnetic circuit of the first unit built is shown inset on Fig.4. It was required to measure the torque-excitation characteristic in a similar manner to that adopted during the earlier flat plate tests, that is, while working under conditions of continuous slip.

5.1 For test purposes the clutch was built into a gearbox, which coupled the rotor output shaft to a spring balance. An electric motor provided with means for controlling armature speed over a wide range supplied driving power to the clutch body. With this arrangement, on exciting the clutch, resultant torque would be absorbed by extension of the spring balance load thereby arresting rotor motion.

5.2 In addition to simple measurements of the torque-excitation relation, it was proposed to observe the effects of speed on performance. Furthermore as motion of the load system was undamped, some comparative information should be obtained on the smoothness in operation of different iron powders.

5.3 Unfortunately quite early in the test programme it became evident that the clutch was unsuitable for use at any reasonable speed of revolution. This was partly due to high unenergised drag, (see Fig.4) a feature later improved by serrating the rotor periphery, but more particularly because of persistent seizure whenever the clutch was energised. Although a number of different iron powders were tried, both dry and mixed with oil, it was not found possible to overcome the fault except by running the clutch at very low speeds of the order of 100 r.p.m. or less.

The characteristic of Fig.5 was obtained in this manner for record purposes, but generally the design was unsatisfactory and further work on the unit was abandoned.

Clearly, centrifugal forces acting on the fluid medium were of greater importance than had been considered.

6 Cylinder Rotor Clutch

To permit the use of a higher working speed, attention now transferred to the cylinder form of rotor construction. A second clutch, incorporating this feature, was built and fitted to the previous gearbox assembly.

6.1 A systematic examination of the clutch performance in relation to each of the available iron powers, conducted in the manner described earlier, showed the device to be a working proposition. While working, energised under slipping conditions, torque transmission was found to be quite smooth at all speeds of rotation up to the maximum of 8,000 r.p.m. obtainable on the test rig. Even dry electrolytic iron proved quite satisfactory for use, an interesting fact in view of earlier experience with the flat plate. The operate and disengage action was rapid and positive; moreover unenergised drag was of negligibly low order.

6.2 Measurement of the torque output while slowly cycling the excitation between zero and a maximum revealed an unduly large hysteresis loop, far greater than would be expected from residual magnetism in the iron circuit. It was suspected that this may be a penalty of using dry powder media, the effect being caused by incomplete relaxation of iron particles in the medium due to lack of a separating lubricant, but after further investigation using iron-oil mixtures this was disproved. A typical hysteresis characteristic using a fluid mixture is shown in Fig.6.

6.3 Torque output for a fixed excitation varied to some extent with rotational speed but to a far lesser degree that with the disc clutch. At no time did this cause erratic operation. The order of the effect depended on the magnetic medium in use, dry electrolytic iron proved to be particularly poor in this respect (Figs.7, 8 and 9), but since in most applications a fixed clutch speed would be used, the phenomenon was considered to be relatively unimportant.

6.4 Dimensions of the clutch rotor had been determined from data obtained during tests on the steel plate (Fig.3) to achieve a torque transmission of about 2 lbs. ins. at a maximum excitation when used in conjunction with sample C iron powder mixed with oil in the ratio of 7:1 by weight. The actual performance will be seen to fall far short of this figure, in fact, a very poor correlation of the static plate results with dynamic performance of the clutch was observed generally. Most remarkably, the order of precedence of the two most effective materials appeared to be reversed (see the 1,500 r.p.m. characteristics of Figs.8 and 9), and again, the torque transmitted by these materials relative to the fluid mixture of Fig.7 was far less than expected.

6.5 It became evident at this stage that the simple methods being applied were inadequate to enable a clutch with a specific performance to be designed. Although some promising results had been obtained, many unknowns still existed and either a considerable amount of fundamental research work had to be done or data accumulated by building clutches for specific purposes. The latter course was adopted as staff was not available for an obviously extensive research programme of this kind, and also because nothing was known yet of the behaviour of the clutch under service conditions.

7 Experimental Servo-Actuator

Work restarted during 1950 with a requirement for an electric servomotor to be used as the control surface actuator of an aircraft in conjunction with the RAE Type B Autopilot. Briefly, the actuator here forms the power output element of an on-off servo mechanism, and, in the proposed form, comprised a continuously running motor driving two clutches in opposite senses of rotation, their output members being geared to a common shaft. Either clutch may be engaged separately by means of a relay to reverse motion of the common shaft.

7.1 It is unnecessary to relate the considerations leading to choice of the magnetic clutch for this application except to say that the high speed response shown to be inherent from previous experiment would obviate difficulties arising from stabilising the servomechanism.

7.2 The actuator was required to deliver a maximum torque of the order of 60 lbs. ft. at a control speed of 5 r.p.m., and to operate wholly from nominal 24 volts D.C. aircraft supplies. Since it is connected to the main aircraft control system, reliability is of the utmost importance.

7.3 A survey of detailed requirements for the clutch to meet this specification led to the following conclusions:-

(a) A cylinder form of rotor construction would be used.

(b) In view of the pronounced effect and vague understanding of high rotational speed on torque transmission, some caution was necessary in selecting the clutch driving speed. 750 r.p.m. was chosen arbitrarily as a suitable compromise requiring a nominal 5 lbs. ins. torque transmission from the clutch. An added advantage in favour of low speed operation was the lower rate of wear on bearings and seals.

(c) Dry iron powder would be used as the magnetic medium:-

(i) in order to simplify sealing arrangements;

(ii) to achieve a high torque output-excitation efficiency;

(iii) to obviate sludging difficulties now known to be presenting major problems with other workers using iron-oil mixtures.

(d) A relatively large rotor-pole clearance of 0.03" was advisable to ensure smooth operation.

7.4 An estimate of the approximate rotor size, (based on test results of the previous cylinder clutch as the flat plate tests were evidently inapplicable), showed that a more compact assembly than that used previously would result from re-arrangement of the magnetic circuit. There was of course some risk that a major design change of this nature may affect the performance adversely in some way but on engineering grounds the risk was considered justified.

7.5 The final arrangements of the magnetic circuit is shown in Fig.10. Two units were built and each subjected to routine tests at a fixed speed of 750 r.p.m. in the usual manner.

7.6 Unfortunately the sample quantity of Salford 'G.L.' iron powder had been used up and in trying to obtain further supplies from the firm we learned that the grade was no longer manufactured. An alternative material supplied, known as 'F.F.' grade, proved to be inferior and was never used.

7.7 Apart from realising only about one half of the designed maximum torque, the performance proved in every other respect to be entirely satisfactory. Smoothness in operation was so remarkable that torque measurements were made with the spring balance directly coupled to a lever arm on the clutch rotor shaft to eliminate gearbox friction. Even then the transmission was completely free of any oscillatory motion.

7.8 A second notable feature was a negligibly small torque hysteresis.

7.9 Efforts were now directed toward increasing the torque output and fortunately in this respect the clutch responded to rational treatment. It was considered, from the torque-excitation characteristic, that the iron circuit, including the powder medium, was operating well below magnetic saturation. The flux-density was therefore stepped up in three stages:-

(a) by reducing the working pole-gap;

(b) by reducing magnetic leakage through the rotor shell;

(c) by increasing the excitation.

7.10 The progressive improvement of torque transmission through the first two of these phases is shown graphically in Figs.10 and 11. Pole clearance was reduced by fitting rotors of different shell thickness. It was found that while a 0.02" gap was permissible, further reduction to 0.01" caused a marked deterioration in smoothness of transmission.

Eliminating flux leakage axially along the rotor resulted in a slightly more complicated construction. Initially the active rotor surfaces formed part of the same hollow cylinder but were separated by 'spokes' formed by drilling a series of holes in the rotor circumference to increase magnetic reluctance. A substantial improvement of torque output will be observed from Fig. 11 as a result of fabricating the rotor in three parts to include a non-magnetic bridge.

7.11 A further increase in torque to realise the design figure of 5 lbs. ins. was brought about by raising the level of excitation. Since the clutch was now approaching saturation, this required more than double the existing ampere turns but the coil temperature rise due to watts dissipated was within permissible limits. Fig. 12 shows the torque characteristic finally obtained as a result of these modifications.

7.12 Two clutches to this final design were now built and fitted to an experimental actuator. This was subjected to protracted performance testing in the laboratory simulating conditions of vibration, temperature extreme and load which could be expected in service. In particular careful attention was given to the day to day torque stability and mechanical reliability during a prolonged endurance test under load.

Some loss of torque output was observed when the actuator was operated at low ambient temperature (-40°C), and some day to day torque variations at normal temperatures was noted but otherwise performance requirements were fulfilled to satisfaction, and flight trials in a Meteor aircraft fitted with the RAE Type B autopilot were put in hand.

7.13 Although only a limited amount of test flying was achieved, considerable delay being caused by aircraft unserviceability, the results indicated that performance was satisfactory and since demand for the actuator was becoming increasingly urgent a production design was initiated. This was laid down without rearranging internal construction of the clutches. A pilot order for reproduction was placed in industry and two models to the production design were manufactured at RAE.

8 Production Servo-Actuator

The contractor's sample actuator and both RAE models were received about the same date. Each actuator in turn was subjected initially to an endurance test by driving the unit from a sinusoidally varying input against a spring load.

8.1 Both RAE models failed after approximately 40 hours continuous operation, the contract sample however completed 100 hours operation with no sign of failure.

The RAE units both failed in a similar manner: total seizure of both clutches in each actuator occurred if the unit was switched off. The drive motor could not be restarted. The clutches could be freed by any means which agitated the iron powder inside the clutch, and the actuator then operated quite satisfactorily unless it was switched off again when the fault repeated.

8.2 The phenomenon had not been observed before on this design of clutch and significantly, the contractor's sample could not be induced to lock completely in this fashion at all.

8.3 A detailed examination of the dimensions and materials used in construction and filling of the RAE and contract clutches revealed no simple explanation for the different performance except that while the contract clutch rotors were fabricated from Swedish Iron, the material used hitherto on all experimental clutches, RAE workshops had been given a concession to use BSS S14 steel owing to non-availability of Swedish Iron.

This was not accepted as a completely satisfactory explanation of the different performance as both materials are magnetically and mechanically similar but represents the only explanation to date. Arrangements are in hand to re-make the RAE rotors of Swedish Iron to prove the point.

8.4 During this investigation it was observed that:-

(a) a brittle black deposit of the order of 0.003" thickness had accumulated on the working surfaces of the magnet poles and rotor. The deposit did not adhere strongly to the surface but flaked off easily. An analysis of the deposit by Chemistry Dept., RAE showed it to be pure iron, free of carbon.

(b) the mean particle size of the iron powder filling had been reduced during the course of endurance testing by approximately 50% in the case of RAE clutches and only about 20% in the contract clutches.

This observation is considered to be significant since previous experience showed the finer particle iron powder more prone to cause seizure than larger particles.

8.5 Continuing this investigation, an attempt was made to understand why iron is deposited on the working surface of the clutches. It was conceived that high local temperatures, which must be generated at the rotor and pole surfaces when clutch slipping occurs, could weld iron particles to the working surfaces. If the powder and rotor were of dissimilar materials the deposit should not form. Tests were made on a clutch fitted with a chrome plated rotor to examine this possibility.

Results were disappointing in that not only was there a considerable reduction in torque transmitted, but seizure again occurred after 35 hours. On inspection, although the chrome plating was still intact, a considerable thickness of deposit was present.

9 Miscellaneous Considerations

9.1 As a result of this work, dry electrolytic iron powder has become well established as the most suitable magnetic medium, of those materials tested, for use in this form of clutch. In order to prevent corrosion a small quantity of Vapour Phase Inhibitor in powder form is being inserted in the clutch with the iron during the filling operation. This has no effect on the dynamic performance of the clutch but, from observations made over the past six months, appears to be an effective rust preventive.

9.2 Six different grades of electrolytic iron were obtained from Messrs. Cohen & Sons recently and each subjected to test in turn in a clutch. It will be observed from Fig.13 that a fairly sharply defined optimum particle size appears to exist and that some advantage is to be gained by using annealed material.

9.3 Torque transmission appears to be relatively insensitive to the amount of iron powder inserted in the clutch. A nominal filling approximately equal to the annular volume of the powder cavity, can be varied as much as ±50% with only minor effect on torque transmission.

9.4 The very poor correlation between static measurements (para 3.0) and torque transmitted by a clutch designed from the results of such measurements has been shown. Evidently the dynamic conditions which exist during normal operation of a clutch play an important part in the torque performance and must be taken into account when analysing the clutching action.

9.5 Although with a cylinder version of the clutch, having its working cavity just full of iron powder under static conditions, one would expect separation of the powder from the working surfaces, and therefore a reduction of torque at high speeds of revolution, the characteristics of Figs.7, 8 and 9, show a marked increase of torque with speed. No explanation for this can be put forward at present.

9.6 Again, no reason can be put forward to explain the large torque hysteresis shown to be present in the first experimental cylinder clutch (Fig.6). Freedom of the present actuator clutches is attributable only to a fortunate choice of construction.

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FIG. 1.

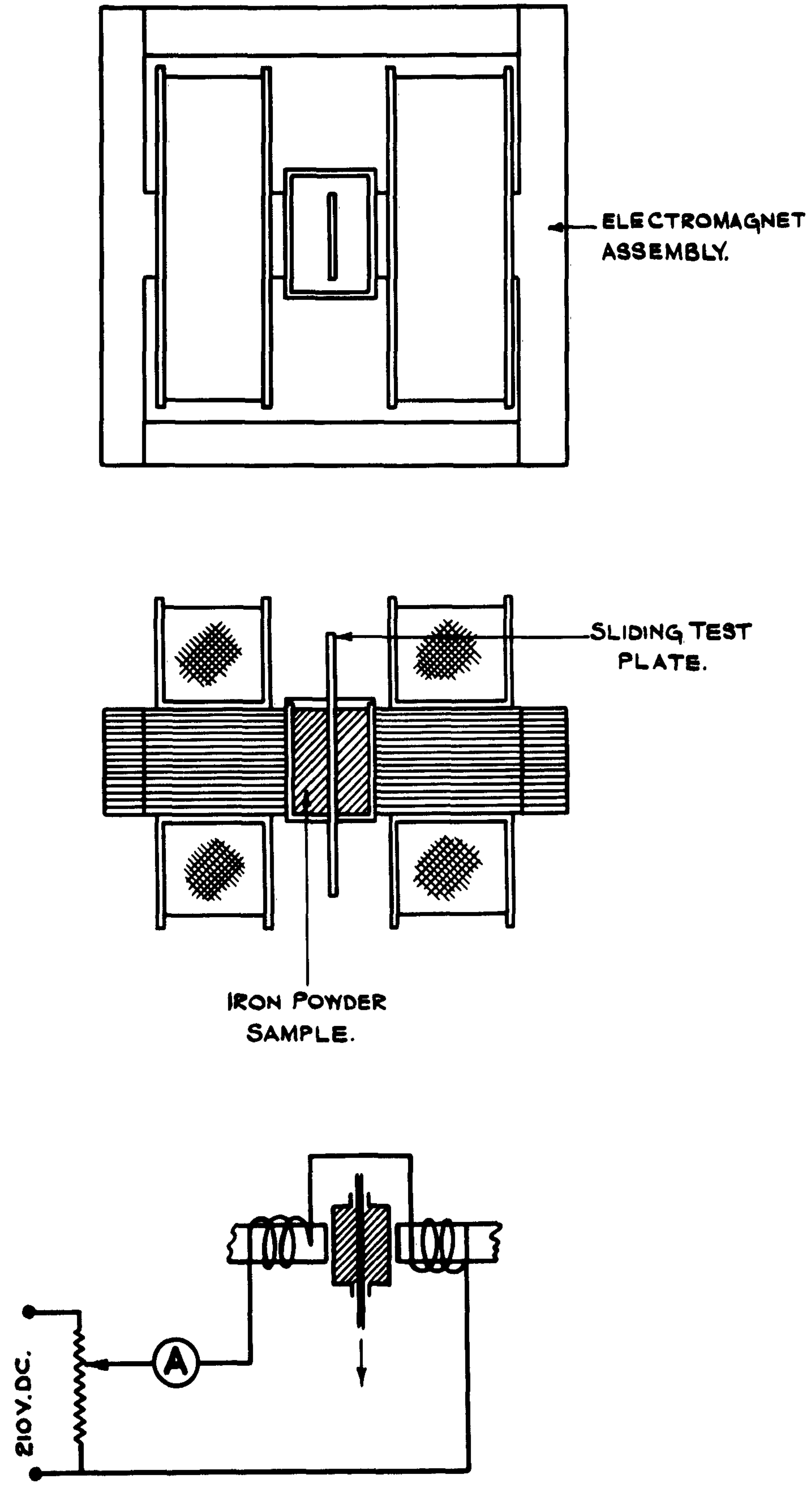


FIG. 1 MAGNETIC CIRCUIT & SCHEMATIC ARRANGᵗ OF PLATE DRAG TEST APPARATUS.

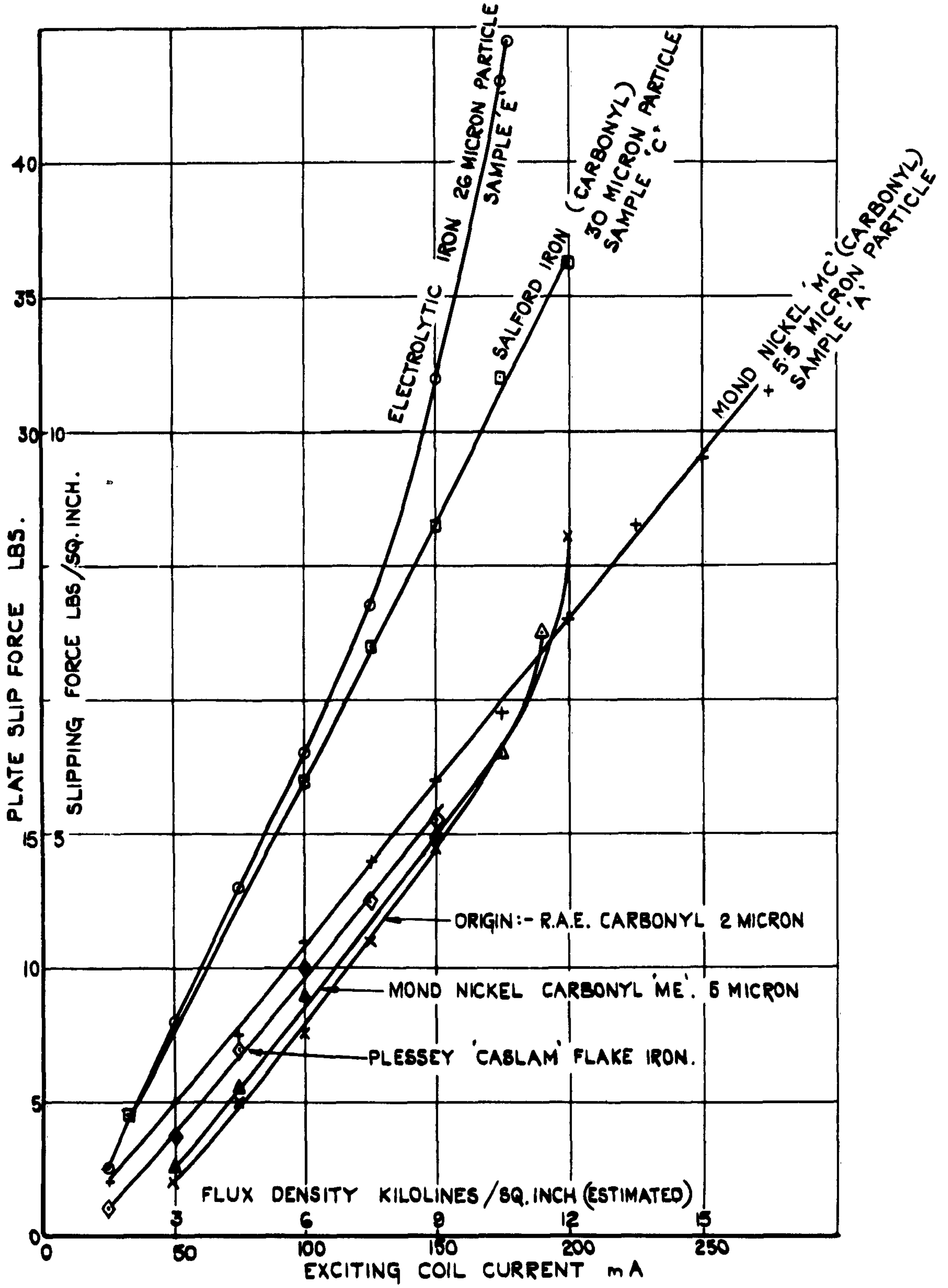


FIG. 2. DRAG CHARACTERISTICS OF DRY POWDERS ON A STEEL PLATE.

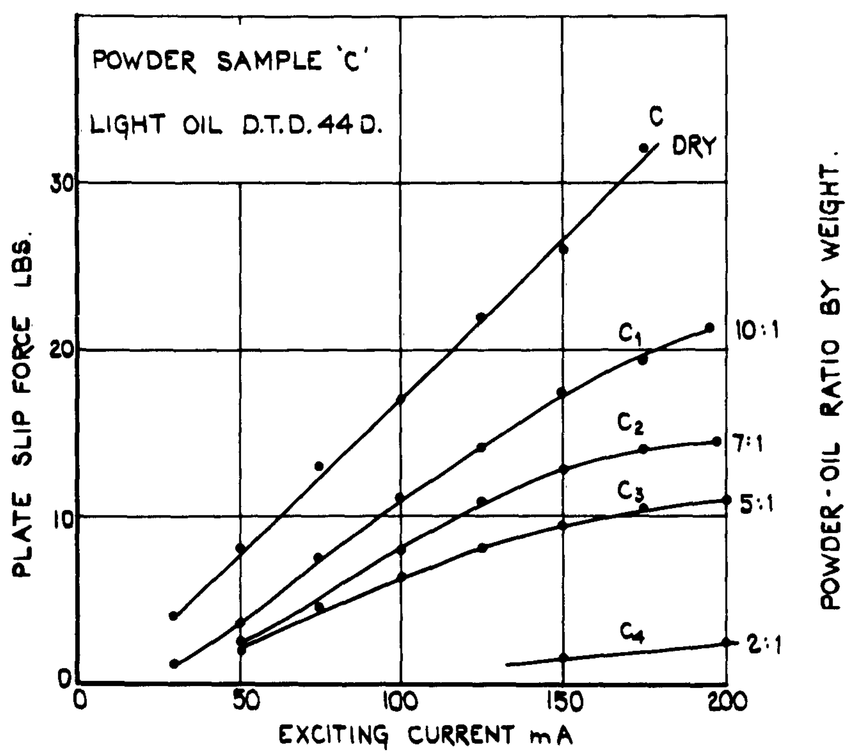


FIG. 3. DRAG CHARACTERISTICS OF POWDER-OIL MIXTURES ON A STEEL PLATE.

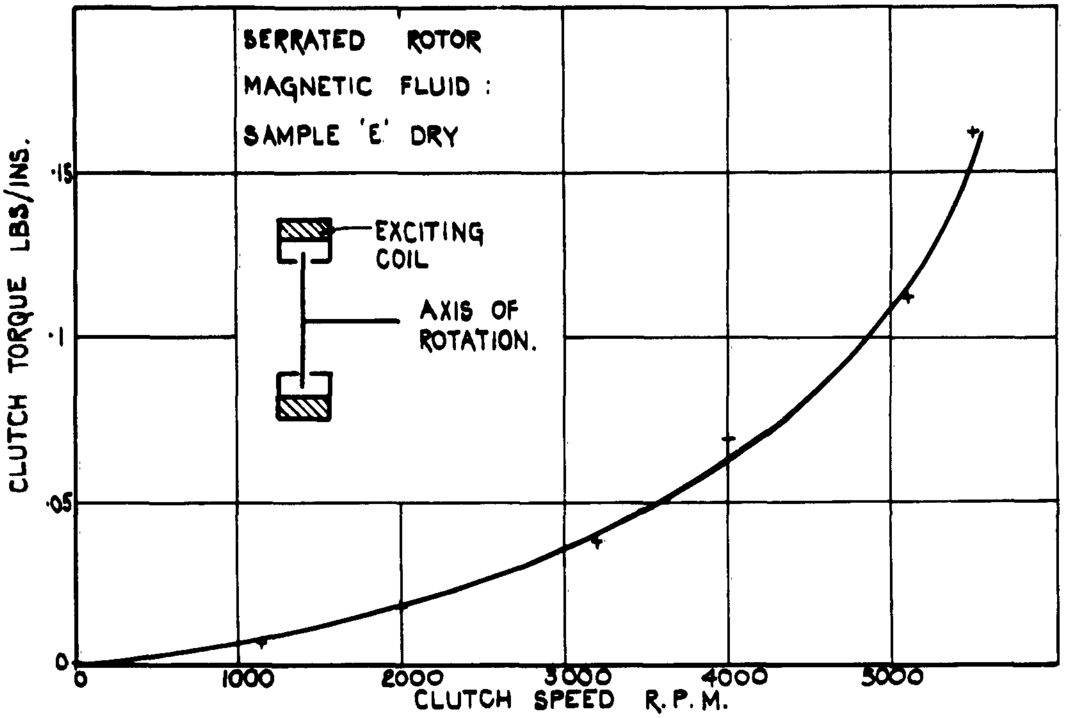


FIG. 4. UNENERGISED DRAG.

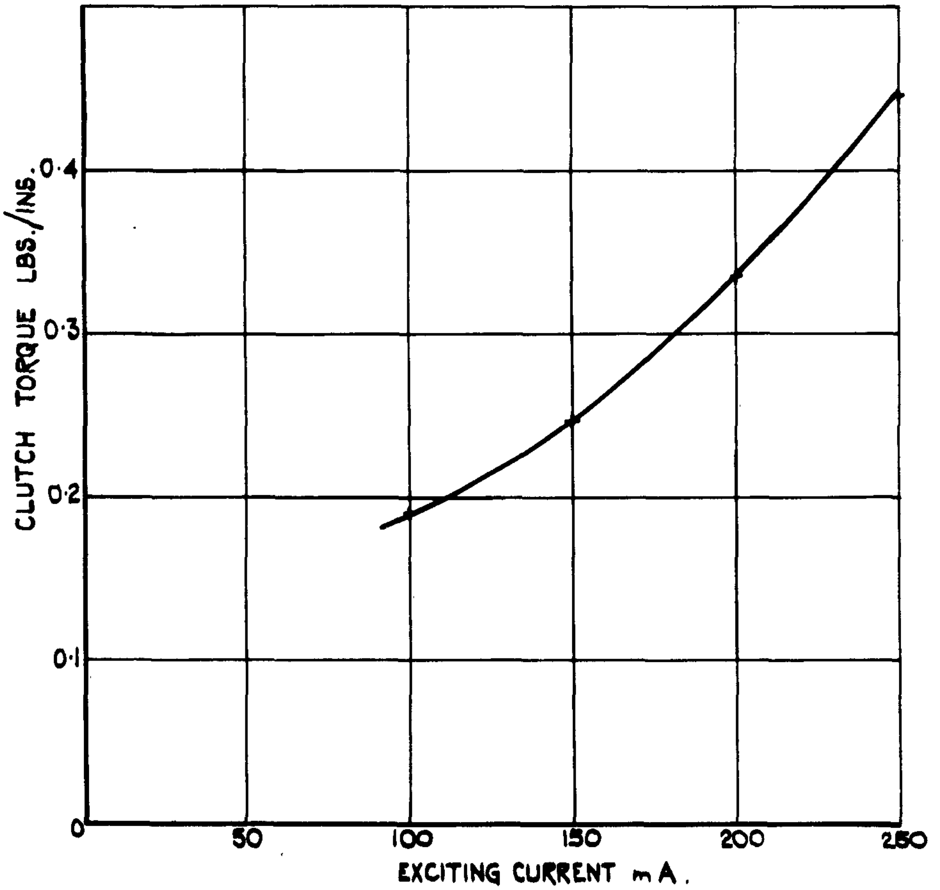


FIG. 5. LOW SPEED TORQUE - EXCITATION CHARACTERISTICS.

FIG. 4& 5. DISC CLUTCH.

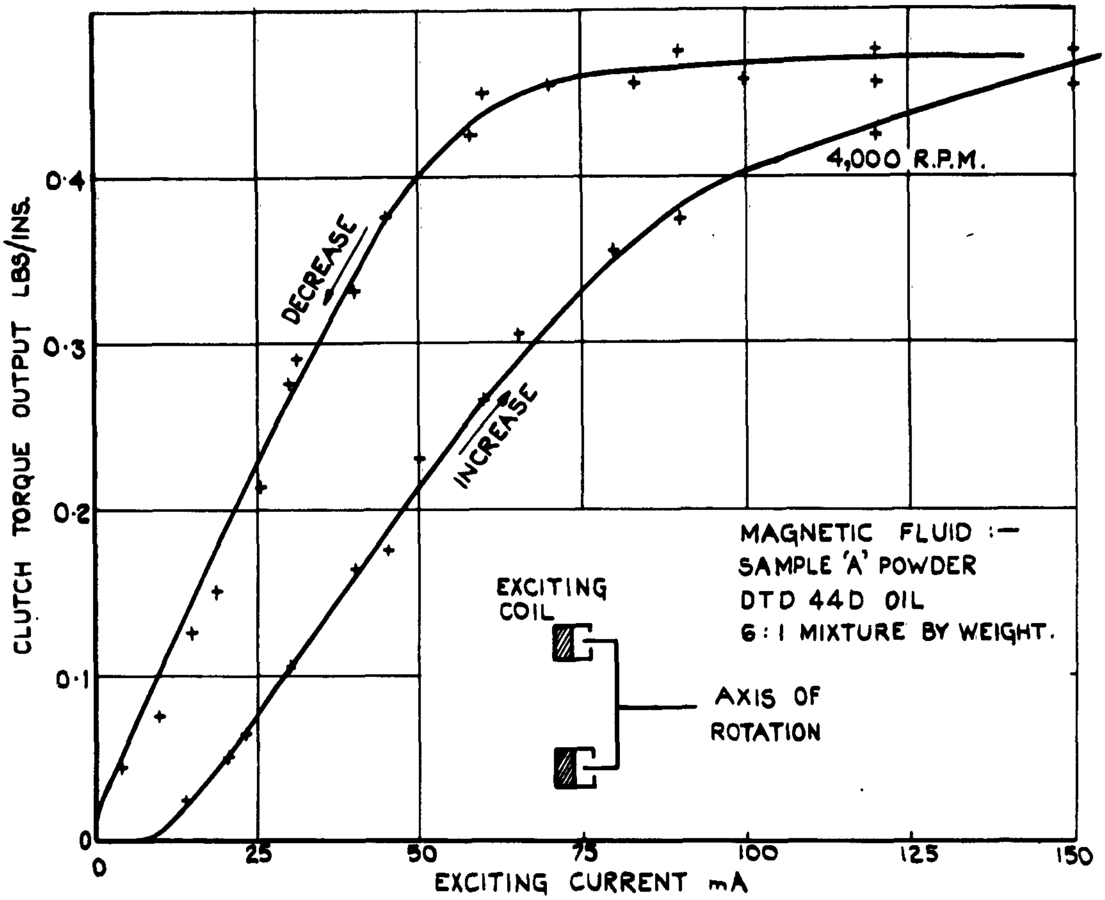


FIG. 6. TORQUE HYSTERESIS.

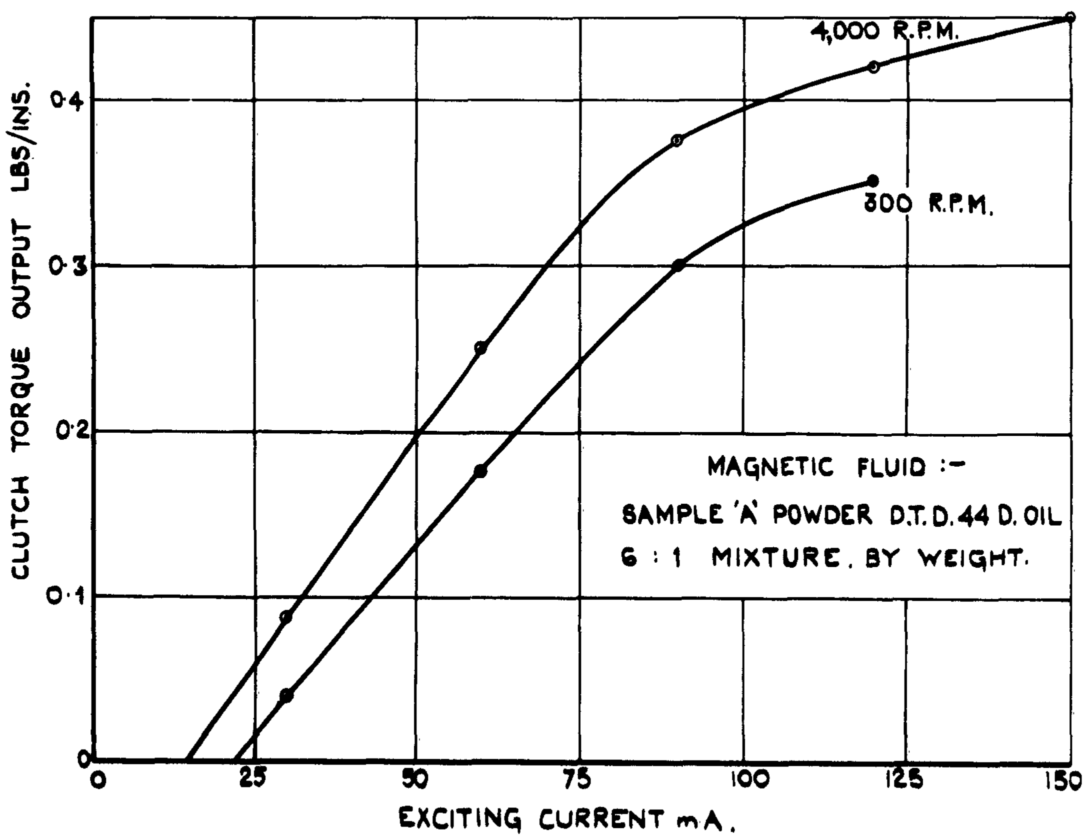


FIG. 7. SPEED CHARACTERISTICS

FIG. 6 & 7. CYLINDER CLUTCH.- WET MAGNETIC FLUID.

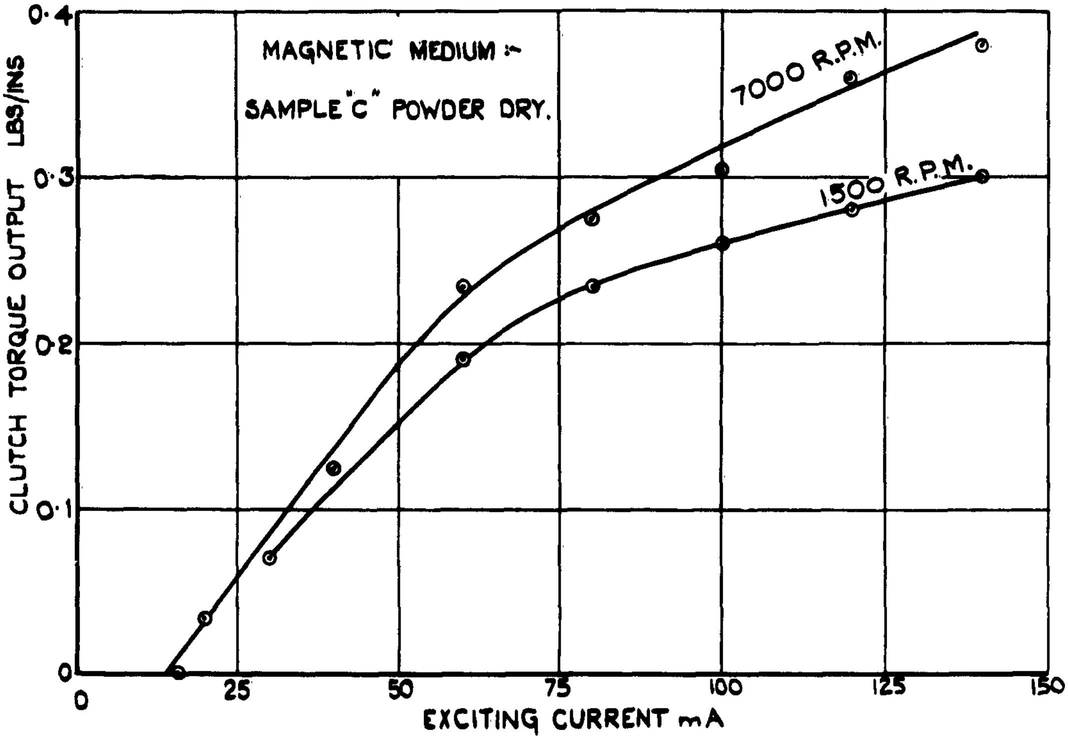


FIG. 8.

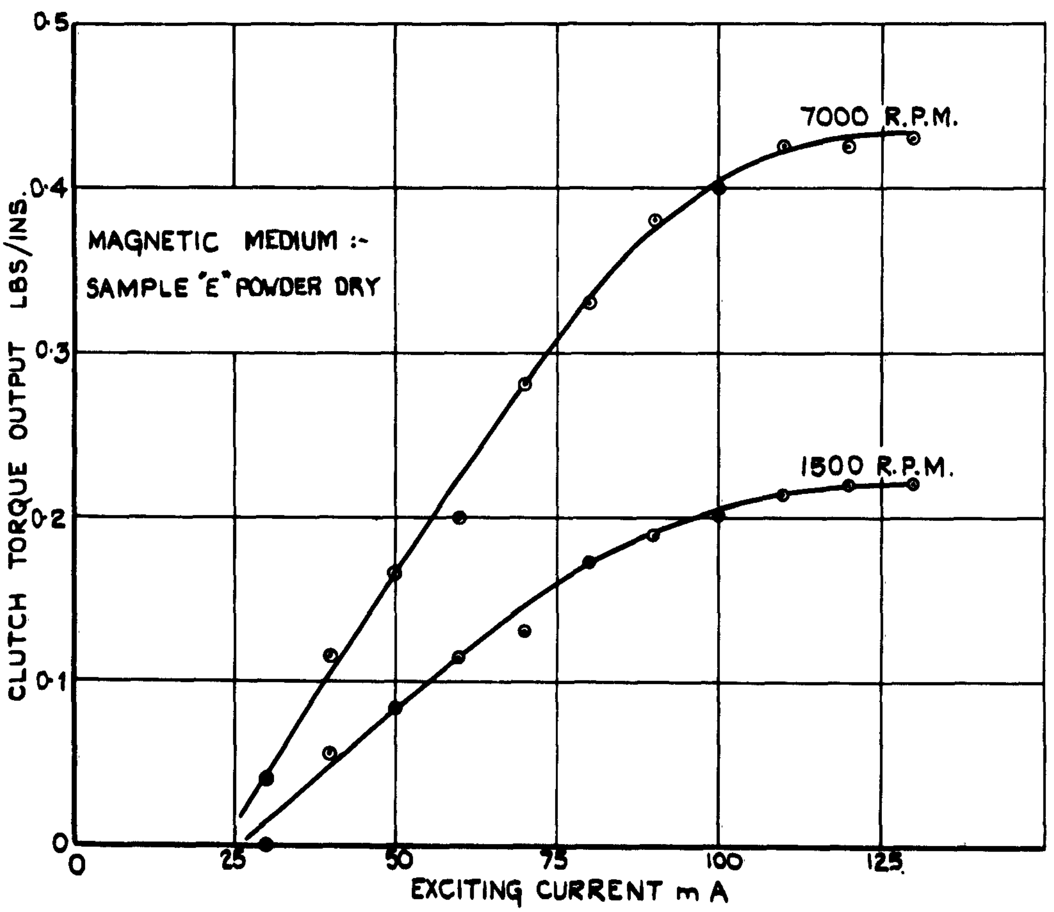


FIG. 9.

FIG. 8 & 9. CYLINDER CLUTCH. SPEED CHARACTERISTICS. DRY MAGNETIC MEDIUM.

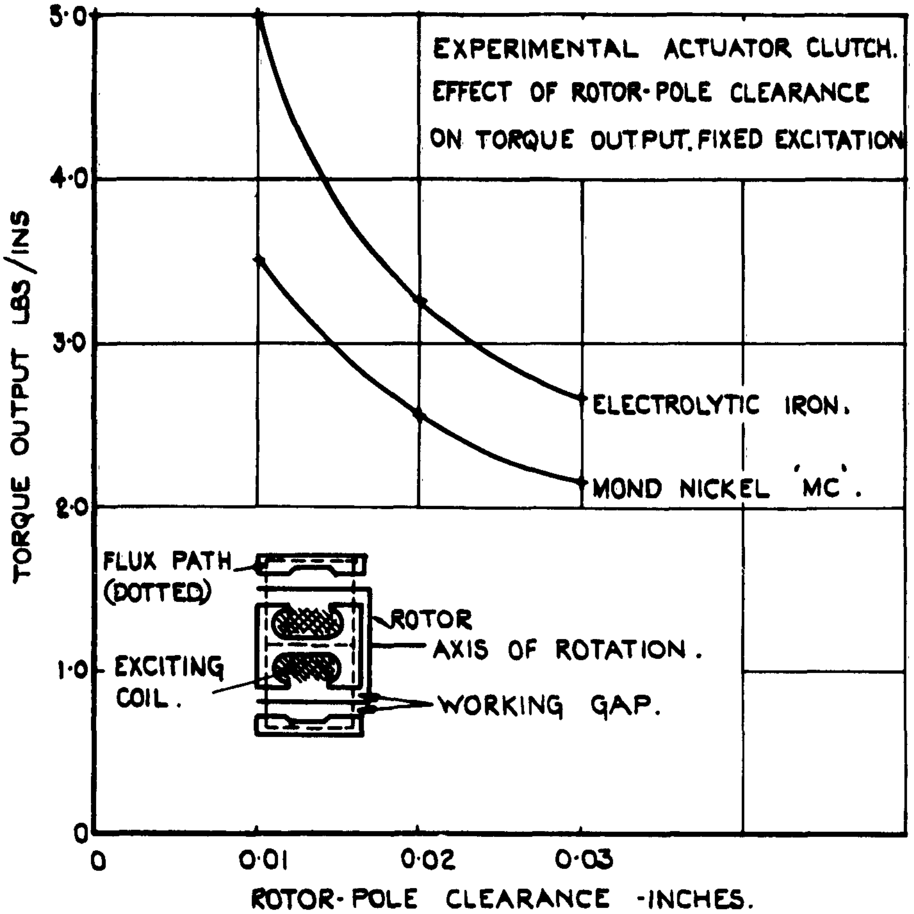


FIG 10

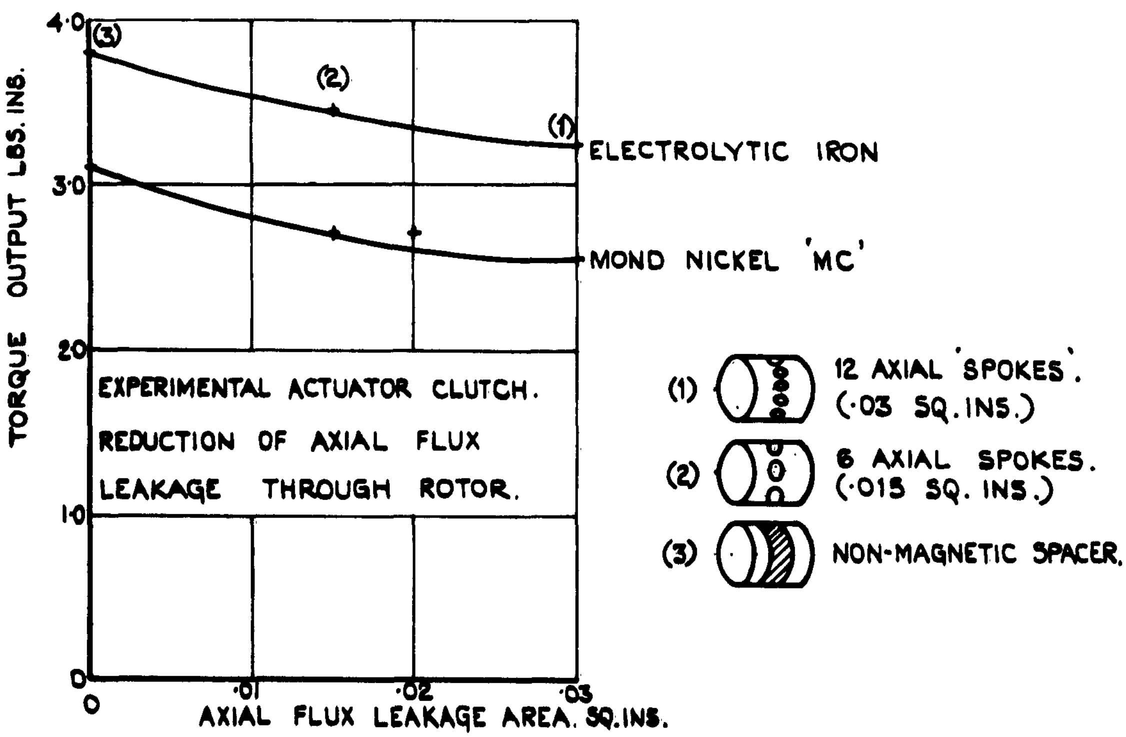
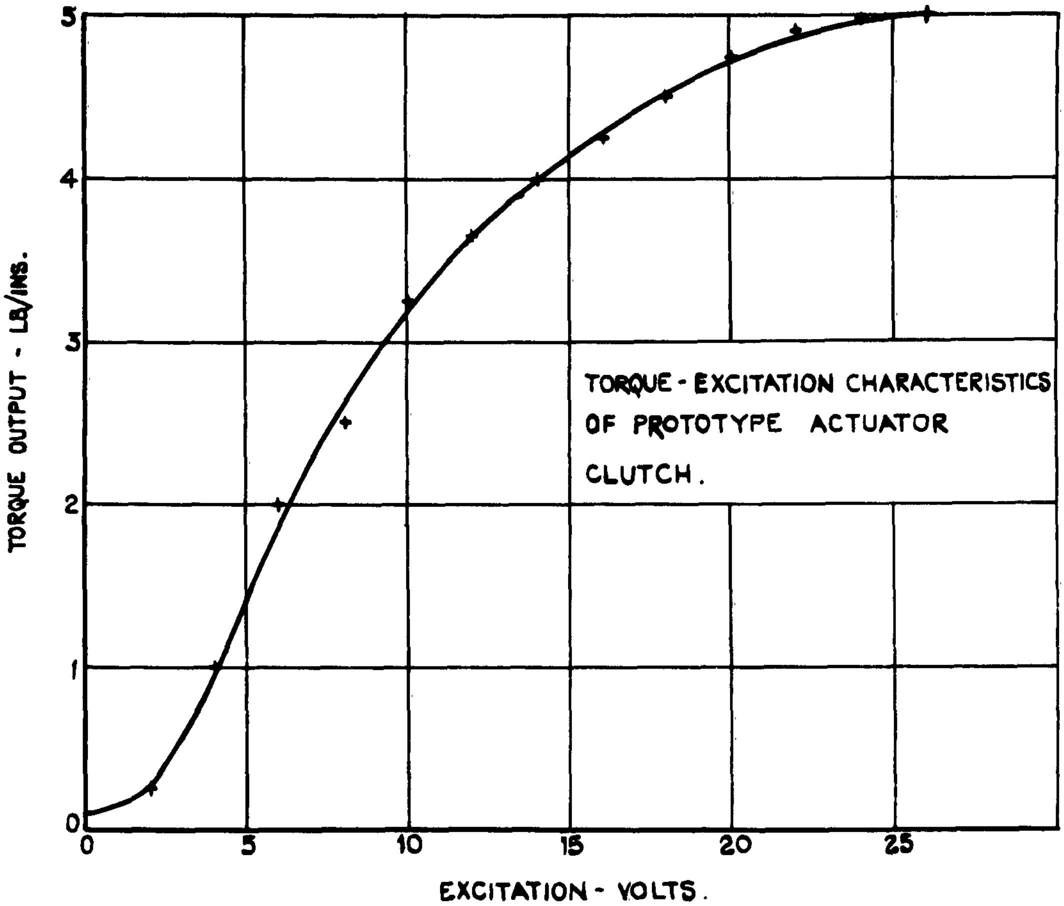


FIG. 11.

FIG 10 & 11.


TORQUE OUTPUT - LB/INS.
EXCITATION - VOLTS.
TORQUE - EXCITATION CHARACTERISTICS OF PROTOTYPE ACTUATOR CLUTCH.
0
1
2
3
4
5
0
5
10
15
20
25

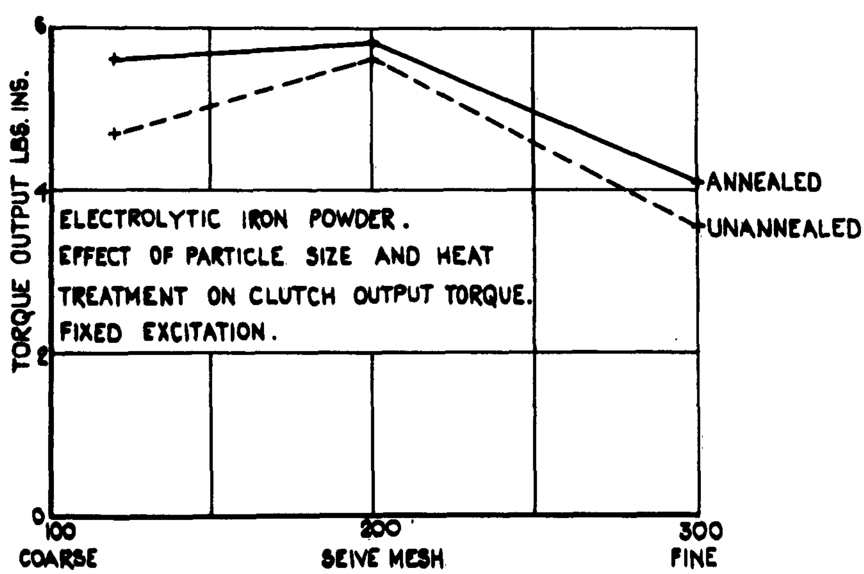

TORQUE OUTPUT LBS. INS.
ELECTROLYTIC IRON POWDER.
EFFECT OF PARTICLE SIZE AND HEAT TREATMENT ON CLUTCH OUTPUT TORQUE.
FIXED EXCITATION.
ANNEALED
UNANNEALED
0
2
4
6
100
COARSE
200
SEIVE MESH
300
FINE

FIG. 12. & 13.

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