A THEORY OF ELECTRICITY

Continued from Previous Issues

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51. Arago's Experiment.

In 1824, D. F. J. Arago [1] demonstrated before the Paris Academy of Sciences that a moving piece of copper plate would deflect a magnetic needle, whereas the same plate when at rest displayed essentially no magnetic influence of anything like comparable magnitude upon the needle. The device used by him to exhibit this effect was a copper pendulum put into oscillation near the needle. The needle then visibly followed the swinging of the pendulum.

This discovery was followed in 1825 by others which Arago reported in [2]. He there demonstrated:

(a) that water, ice and glass had weak magnetic fields;

and, more significant to the present discussion:

(b) that rotating discs of copper, zinc, brass and lead generated a field that was considerable, and much greater in deflecting a permanent magnet than the minute field they possessed when at rest.

The Paris newspapers reported the remarkable discovery and the news of it was taken by Gay de Lussac to London almost immediately. Babbage and Herschel[3] there repeated Arago's experiments, as well as Christie [4], the latter also assisting in the redo and independently challenging some statements made by Arago to the general effect that all materials, including non-conductive ones, did the same thing to a greater or lesser degree. Christie found this was not so. A careful study of Arago's paper shows that he really did not experimentally justify this broad assertion and that, in fact, it was rather a newspaper statement than his but all the same he acquiesced in it. Today we accept that all materials have some degree of magnetic permeability, so, after all, Arago has been vindicated.

It is also stated by Faraday [5, §130, p. 159] that someone named Harris reproduced Arago's effect:-

> ... *with wood, marble, freestone and annealed glass, but obtained no effect with sulphuric acid and saturated solution of sulfate of iron, although these are better conductors of electricity than the former substances* (i.e., metals and carbon).

Faraday fails to give any reference for Harris' paper, so we cannot now locate it.

Babbage and Herschel, incidentally, showed that the liquid conductor, mercury, did exhibit the effect.

The Toth-Maatian Review, 3101 20th Street, Lubbock, TX 79410, U.S.A.
Vol. 9, #2, July 1990, pp. 4413-22.

52. Faraday's Experiment.

Faraday became interested in Arago's discovery and in conjunction with Christie, he subjected it to a thorough experimental investigation which is reported in detail in [5]. It is not our present intent to review Faraday's paper in any detail, but we will reserve such a discussion, if any, for a later installment when the reader may better appreciate the comments made concerning it. For the moment, we limit ourself to two important quotations taken from it and some brief description of the experiment and what Faraday's conclusions were. The first of these quotations is [5, §81, p. 147]:

> *... the effect is so powerful, that magnets or plates of many pounds weight may thus be carried around.*

This is indeed so, and the writer will vouch for it, based on his own experience. It is really quite surprising how great the forces of such magnetic drag are.

The second quotation is taken from Faraday's summary near the end of his report [5, §133, p. 160]:

> *I have never been able to produce any sensation upon the tongue by the wires connected with the conductors applied to the edges of the revolving plate or slips of metal. Nor have I been able to heat a fine platina wire, or produce a spark, or convulse the limbs of a frog. I have failed also to produce any chemical effects by the electricity thus evolved.*

One might be amused in our present age that has benefitted from the instrumentation developed for measuring electrical current and potentials over the century and a half since Faraday's time, by the methods he used. However, the tongue-test is really quite a sensitive indicator and the author can himself vouch for it that very minute currents can be detected by the evolution of gas bubbles in an electrolytic cell. It is as sensitive a measuring device for current as any that is available. Currents that are too small to register on the minimum 1 microampere scale of our digital ammeter, show up in time with the gas bubbles liberated at the plates of a simple water cell. In so far as sparks are concerned, one can observe them, if careful in observation, and Faraday was a careful investigator, certainly, from a 1.25 V battery. Thus, the order of the electrical energy which Faraday failed to detect, is less than a microwatt. We comment, then, that it is remarkable that forces in the range of 25 kg were exerted in his experiment by currents, the only trace of which he, Faraday, was able to sample and did detect, involved less than a microwatt of energy.

His method of detecting this small amount of current drawn from the rotating disc requires some comment. It is described by him in full detail in his very thorough description of what he did. He constructed a torsion galvanometer by pushing two magnetized sewing-needles through a dried straw suspended by a silk thread. A wire coil of some 16 or 18 turns was placed under this balance and it then responded to the small amounts of magnetic flux that were generated by the current drawn off his rotating disc. He provides us with a sketch of this galvanometer, reproduced here as figure 52.1 from his report.

Figure 52.1.

The aging original of this copy is very faint and it has been difficult to secure any reproduction of it at all. We hope what we have will survive the printing process. In case it may not, Faraday's diagram shows the two needles suspended horizontally one above the other on a hanging thread with the wire coil, placed horizontally also, between them.

Of the apparati employed by him, there were a number of variants, though only one of these has subsequently made it into the textbooks. This latter was a copper disc that was made to rotate between the poles of a strong permanent magnet that was the property of the Royal Society. The magnet was a curiosity for its time, capable of lifting 100 pounds. In another series of experiments, a rectangular copper plate was pushed linearly between the poles of the same magnet, in place of the rotating plate. Faraday points out that the rotating disc just provides a continuous motion for such a rectangular plate. In a third variant, a copper ring was used rather than the disc, with the brushes rubbing against its outer and inner lateral faces.

The systematic, innovative and imaginative methods of Faraday are much to be admired as well as the thoroughness with which his investigations are pushed in so many directions. Also, his deductions are lucidly made, well supported by experimental evidence and, moreover, convincing.

For the brushes or contacts to the moving metal parts, he coated them first with mercury, forming an amalgam that apparently made a better electrical connection than the bare metals. They were simply hand held against the moving pieces.

Further particulars are given in adequate and complete detail and it would be quite possible to repeat today, a century and a half later, exactly what he did by following his instructions. It is an excellently composed description of all that might be pertinent to the experiment.

We shall not go into further details but refer the interested reader to the original paper for them.

53. The Purpose in Redoing Faraday's Experiment.

Faraday's experiment is seldom discussed in textbooks and when it is, the impression is given that if a copper disc is just driven round between the poles of a magnet, a current arises between its center and outside periphery. Sometimes a cut is shown of such a disc on an axle held by a stand and driven by a pulley. A short segment of the edge of the disc dips into a trough of mercury out of which a wire leads. A second wire is then connected to the metal supports for the axle. Then a horseshoe magnet with its poles turned inwards is attached by an adjustable clamp to the stand and the disc passes between the poles. The implication is that simply revolving the disc causes current to flow through the wires that are series connected to a meter.

The author is still pursuing the question of whether electrical current is a true current of massed particles, electrons, through the medium conducting it, or whether it is some activity (such as heat) that propagates among the molecules. Our two previous attempts at resolving this basic question surely, have become bogged down in a veritable miasma of illogicalities uncovered in the existing notions about electromagnetism. Principles have simply been enunciated which when we follow them out have led to the most patent of absurdities. There have been discovered misinterpretations of experimental facts and those very experiments have been found so poorly done that they should not be given the slightest credence, let alone being relied upon to structure theories over them. Then, theories have been developed on such shaky foundations without any effort being made to verify carefully whether what is taken as cornerstones are anyway solidly based. Priestly's pint-pot determination of the inverse square law is an example in point. As we come to our own investigations, we turn up all sorts of questions - some of enormous scientific interest that would demand a lifetime to resolve - that are, however, ancillary distractions from our original line of inductive investigation. In the interest of singleness of purpose we are under the necessity of bypassing these topics until the original question is answered; hopefully, we might return to them at some later time.

The errors that have been uncovered are so numerous at the fundamental level in accepted electrical theory that one can scarcely get started at correcting one of them without finding himself confronted with more. It is worse than the mythical Hydra which when one of its heads was lopped off, grew back nine others to replace it. We cannot even decapitate one head before the other nine appear to make up ten.

For the moment, it is necessary to back away from the previous efforts to settle this question of whether electricity be flux or activity, as they have led to still worse perplexities. We are, then, taking a new tack here, having got nowhere so far following the previous directions.

Our present thinking in relation to the Arago-Faraday experiments is that if the electron be a massed particle, when it exists as current through a rotating metal disc, it should migrate preferentially under the action of the centrifugal force to the outer rim of the disc, while the vacancies left behind would congregate to the axis of rotation. Presumably, the action of the magnetic field involved in the Arago-Faraday experiments is to stir the 'free electrons' latent in the copper metal, out of its lattice. The type of mechanical Hall effect to be anticipated might be expected to have the following characteristics:

(1) the charge drawn from the circumference ought to be negative, and that at the axis positive, under all circumstances whatever the direction of rotation of the disc might be;
(2) the potential difference would vary as the square of the angular velocity, ω, in accordance with the formula for centrifugal force:

$$F = m\frac{v^2}{r} = \frac{m(\omega r)^2}{r} = m\,\omega^2 r \qquad (53.1)$$

(3) the potential would vary linearly and directly with the radius of the disk;
(4) the potential would depend on the mechanical action and be fairly independent of the resistance and other electrical properties of the disc, but the quantity of current generated would depend greatly on these properties.

Were such facts experimentally verified, even approximately so, there would be strong support given to the massed-particle electron hypothesis. On the other hand, if they did not appear to some extent, then a fairly clear counter-indication to such an hypothesis would be provided. Most particularly, if (1) is violated, then the negative conclusion is likely. Be it here acknowledged that the author is fully recognizant that Faraday did discover that reversing the direction of rotation of his disc reversed the direction of current flow from + at the circumference and - at the axle, to - at the circumference and + at the axle, so that (1) is violated already; significantly so in fact, if Faraday's observations are credited. However, we find reason to doubt somewhat whether Faraday actually ever saw the currents that are generated by the disc's rotation. We therefore continue the investigation, in despite, determined to see for ourself.

Moreover, if we credit Faraday's explanation that the currents he observed are due to a conductor crossing through the flux lines of a magnetic field, thereby generating eddy currents in the plate according to the same principle by which a wire filament passed through a variable magnetic field evidences a potential difference at its two ends, then it may turn out that these eddy currents overwhelm the mechanically generated currents we are concerned with. Nevertheless, mechanical currents should yet superpose on the magnetically generated currents. Faraday's explanation, we grant, is simple, clear and reasonable, as well as quite convincing and the author is much inclined to credit it. There is, however, no substitute for first-hand awareness.

54. Experiment #37.

An experiment has accordingly been undertaken to explore the Arago effect in relation to the question in hand. The design of it is described in this section, the outcome in the next. It has not turned out successfully to date and a better piece of equipment will have to be constructed before any definite determination is possible, but, despite this, what has been attempted already is of interest on account of the very failure of it.

We begin by describing several permanent magnets used. In the more important case a pair of very strong, ferrite magnets were employed, resurrected from a permanent field electric motor, very probably the drive motor for an automobile windshield wiper. These magnets were already bonded to soft iron plates that acted as the keepers and this bonding did not interfere with their magnetic properties. The original cylindrical, concave inner surfaces were ground flat and when the two flat surfaces were brought into contact, it required a pull of about 20 kg to separate them. The keeper plates were machined into an L-shape and the short arms of the L were welded together at A as shown in figure 54.1 which is to actual size. The N- and S-poles of this magnet were adjacent but held apart after the weld by a gap of 8 mm, in which the disc was made to revolve. The magnet is thus not a true horseshoe magnet as was Faraday's, but its field is much more uniformly linear between the gap, with sharply defined lateral edges to it; though the keeper does have a field more of the horseshoe type.

Two additional magnets have been employed, much weaker than the first. These were constructed of flat, circular, ceramic disc magnets held by iron screws to a wooden frame, as illustrated in figure 54.2 that is also to size. The gap between the magnets was 3 mm and the separating force required about 2 kg pull. In the first of these, the N-, S-poles were adjacent; in the second, two N-poles were opposed to one another, instead. Thus, the forces between the two magnets were attractive in the first instance, repulsive in the second.

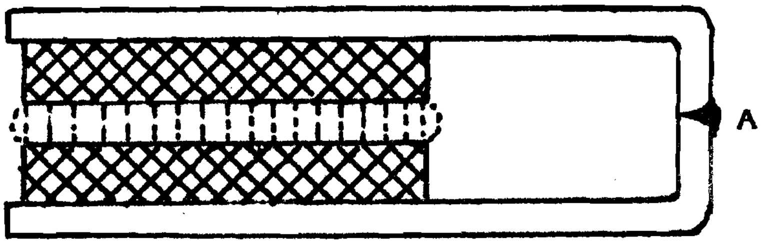


Figure 54.1.

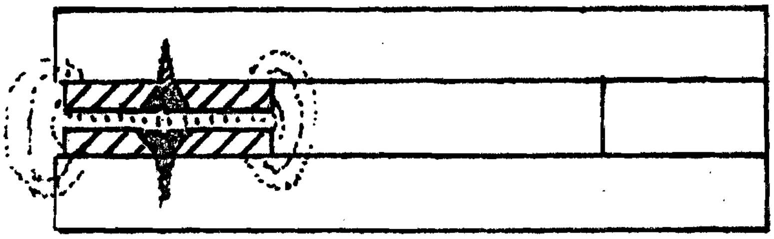


Figure 54.2.

An aluminum disc 7.5 cm in radius was cut from 20-gauge aluminum sheet. The reason for its thinness as compared to Arago's, Faraday's, Herschel's and Christie's discs, which were of heavy metal, is that we have learned that the thinner the metal, the truer it runs at high rotational velocities, avoiding the vibrational problems the thicker pieces are subject to. It was bolted to a steel mandrel with insulating washers separating the two pieces so that there was no electrical electrical connection between them. The mandrel was then affixed to the shaft of a high speed, DC motor capable of turning 14,000 rpm under no load conditions. This motor is rated at 1/40 hp at 12 V operating potential but will run without damage at 40 V and at much higher speeds accordingly, developing greater horsepower. Its speed is easily regulated by a rheostat in series with it. The disc was mounted horizontally and the magnets hand-held so the thin sheet of aluminum passed between their gaps. The assembly resembled a fast-turning record player; c.f., figure 54.3. The brushes were constructed of about a dozen strands of fine, but stiff, copper wire bound together. These were secured by clamps to a plastic bridge located radially over the flat surface of the revolving disc beneath it. The surface of the aluminum was burnished to brightness before the experiment to remove the inevitable non-conducting oxide. The brushes merely made frictional contact with the plate. The use of mercury and amalgamation was thus avoided. When the disc was at rest, the resistance was about .03 ohms but when it revolved to full speed this increased to about 25 ohms, as directly measured by a meter. We considered this to be satisfactory contact.

One brush was located as close to the axle as the mandrel allowed; the other could be moved about in its position but was generally held close to the periphery about 1 cm inwards. It could not be brought to touch against the outer edge as the sharp metal of the disc would just saw it in two in a few revolutions. This arrangement differs from the other investigator's in this detail; they were able to make edge contact with the disc because of the thicker plates they employed.

It was arranged that the magnet could be located anywhere around the circumference either at A, as shown in the figure, or in the reflex angle BAC, but through an unfortunate oversight the supporting bridge for the brushes was placed too close to the disc and prevented the magnets being inserted under it on the direct line between them or in the acute angle between B and C. This error has to be corrected but it is more difficult to do practically than the reader may realize as the plastic bridge is cemented into place on the supports not shown.

55. Initial Result of the Experiment.

It is to be emphasized that the result to this time of writing is provisional. The flaw in the design of the apparatus is significant and until it is remedied and a more powerful motor used, nothing can be definitely inferred.

The magnetic drag is considerable and far greater than ever anticipated. In this we are entirely in agreement with the first quotation from Faraday's report. As a consequence, the motor could not be got up to speed beyond some 1000 rpm. After a minute or so of so operating, the overload protection switch would open and the motor halted. This piece of apparatus is therefore useless and another will have to be consctructed from scratch. We will then use a $\frac{1}{2}$ hp, 3520 rpm AC motor that we have on hand but this has the disadvantage that its speed is not variable. We do not doubt that this more powerful motor will snatch the stronger magnet right out of the hands and pitch it across the room if it is hand-held. Some sort of strong, but adjustable support for it will have to be constructed.

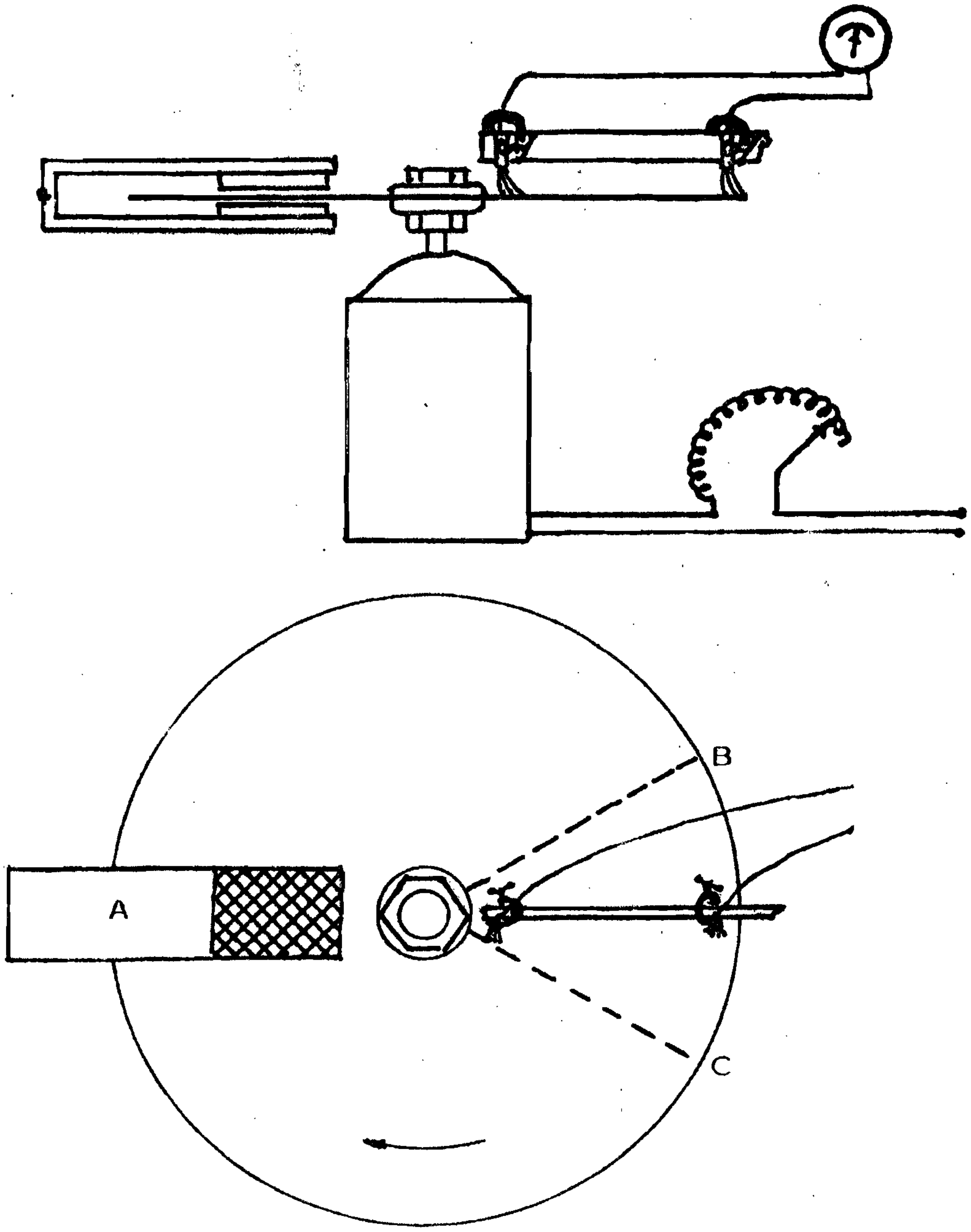


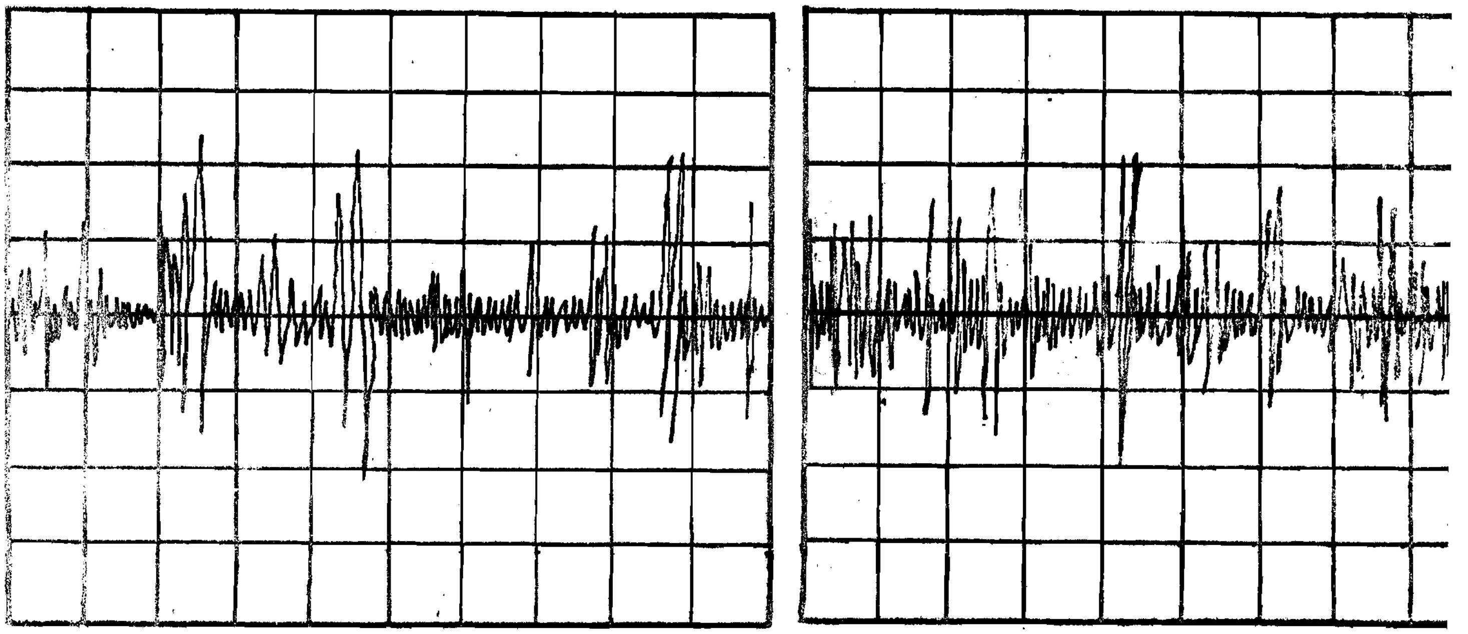
Figure 54.3.

Using the weaker magnets the small motor will turn at an acceptable, but still reduced, speed.

At the time of writing, we have been quite unable to obtain any indication of current flowing between the brushes, no matter where they are located or where the magnet is held within the possible range of positions indicated.

A digital microammeter, sensitive to a single microampere, was connected in series with the brushes and maintained a null reading except in one instance when it rose momentarily to a dubious 3 μa. This agrees again with the second quotation from Faraday. When the multimeter was switched onto the millivolt scale with a minimum 0.01 mv reading, it gave a continually variable and random reading anywhere between +200 mv to -200 mv, quite independently of where the magnet was placed or whether it were even present.

The cause of this variable voltage reading was uncovered as soon as the signal was examined with an oscilloscope. The brushes generate small electrical potentials as they scratch on the aluminum disc. It was impossible to photograph the random, highly variable and rapidly oscillatory traces, so that we can present the reader only with laboratory sketches. These are faithful illustrations of what was visually easily observable. Figure 55.1 (a) shows what occurs without the magnet in place; (b) when it is present. It is seen there is no remarkable difference between the two instances. The DC component in the second figure is negligible, if present at all. The gain was set at 1 V/cm and the sweep rate at 1 msec/cm; the rotation rate of the disc was unknown but perhaps 1000 rpm.



(a) Figure 55.1. (b)

56. Comments.

The experiment, so far, has failed to shed any light on the question under investigation. The only thing that can be said is that if electrons are dislodged from a metallic lattice by a magnetic field, according to the generally accepted model of today, they have already fallen back into it and become fixed there again before the disc has rotated some 10° or so from the zone where the action might be expected to be taking place.

On reading Faraday's report carefully, he claims the current can be sensed by his galvanometer for

... a considerable distance, i.e. 50° to 60°, on each side of the place of the magnetic poles.

Though the author was unable to physically position the magnet in the direct line between the brushes, he certainly did within 50°. Nothing came out of it so great as one microampere. However, final determination must be reserved until after the necessary changes have been made in the apparatus.

To produce, by means of an electromagnetic field, as much force as arises in this experiment we estimate would demand a current in the range from 1 to 10 amperes. If we agree with Faraday that this Arago force is due to eddy currents in the metal, one wonders why so disproportionately small an amount of them can only be sensed.

The disc runs basically true and undeflected between the poles of the magnets, though it is flexible enough to be deflected easily by a finger pressed on its surface while it is rotating. This is true even if the magnet is moved up or down off center so that the disc is almost in contact with either pole. If there be a normal component to the drag force, it is small.

Despite running the disc for some time it did not become warm to the touch, a very surprising result we have repeatedly verified. The eddy currents do not seem to dissipate their energy in heat as one might expect, at least not noticeably so. We remark that none of the early investigators has mentioned the slightest thermal effect as associated with the phenomenon. If an equivalent frictional drag were produced by the rubbing of a pad or piece of emery paper against the rotating disc, it would most certainly evidence some heating. An ampere of current from a battery maintained through contacts of the same area as the magnets, would heat the metal to redness or burn a hole through it. Let us not forget that the drag on the small motors was great enough to shut them down in a few seconds through the thermal cut-off, burn-out prevention devices.

Perhaps these questions will resolve themselves clearly when the apparatus is adequately improved. In the meantime, the Hydra has just burgeoned nine more heads. However, it is not essential to the question actually in hand that the current be self-generated by the revolving disc.

Finally, we feel justified in asking if the minute current sensed by Faraday may not have resulted from friction between the amalgamated surfaces of his copper disc and the contacts to it.

56. Pearce's Experiment.

In a telephone conversation with Mr. Pearce, contributor to this publication, he raised the question of what might occur in Faraday's experiment if the magnetic poles were arranged to give repulsive forces rather than attractive. His remark was made independently of any awareness that the above experiment was then just begun and in its initial stages of preparation. The author had not mentioned to him what we were about. All credit for the idea is entirely due him and we have simply implemented it to save him the trouble, as it is easy to incorporate it into our own attempts.

For this purpose the third magnet with two poles of the same type facing one another was constructed. On using it in the same way as has been described above, we also have not been able to obtain other than a null result, so far.

References

[1] The report of the experiment apparently appears in the Procés-Verbal of the Academy, dated March 7, 1825, but we have not seen it. The reference is secondary taken from Arago's later paper [2] of 1826, p.220.

It has been most difficult tracking down the original source material not only for this but for [2 - 5] below. Never have there been so many erroneous bibliographical references associated with papers as have been encountered here.*

We do have copies of all of [2 - 5] in our files and if there is sufficient interest with the readership to request it, they can be reprinted in some subsequent issue of this periodical.

[2] Arago, D. F. J.: **Note Concernant les Phénomènes Magnetiques Auxquels le Mouvement Donne Naissance,** Annalles de Chimie et de Physique, V. 32, Ser. 2, pp. 213-23, 1826.

[3] Babbage, C. & Herschel, J. F. W.: **Account of the Repetition of M. Arago's Experiments on the Magnetism Manifested by Various Substances During the Act of Rotation,** Phil. Trans. Roy. Soc. Lond., V. 115, pp. 467-96, 1825.

[4] Christie, Samuel Hunter: **On the Magnetism Developed in Copper and Other Substances During Rotation,** Phil. Trans. Roy. Soc. Lond., V. 115, pp. 497-509, 1825.

[5] Faraday, M.: **Explication of Arago's Magnetic Phenomena,** which is §4 of a fuller paper on electricity; Proc. Roy. Soc. Lond., V. 122, pp. 146-62 including plate III which faces p. 131, 1832.

* The reference given in this J. p. 3921 for [5] is incorrect and irrelevant to the topic.