THE FARADAY PARADOX EXPERIMENT

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OBJECTIVE

To investigate the emf produced by a disc rotating in front of a bar magnet, as a function of rotation of the magnet itself and routing of the brush connecting wires.

INTRODUCTION

Michael Faraday did a series of experiments in 1851 where he rotated a disc in front of a bar magnet, and found that it produced an emf because of the motion of a conductor in a magnetic field. Paradoxically, he found that the same emf was produced even if the magnet and the disc were fastened together and co-rotated. He explained this by saying that the magnetic field should be regarded as being "fixed in space", notwithstanding the rotation of the magnet itself. Faraday did not report any effects based on the precise routing of the wire connecting the pick-up brush to the galvanometer, presumably because he did not observe any such effects.

In 1998 a paper was published by A.G. Kelly[1], where he reported no effect from re-routing the pickup wire when the magnet was stationary. However, he reported a substantial effect when using a co-rotating magnet. In fact, by careful routing of the wire, he was able to reduce the emf to zero within the accuracy of his galvanometer.

Such a finding would have some very profound implications. Two different emfs from the same brush could be used to drive a current through a load, even though the brush itself were removed from the experiment. This would lead to a brushless homopolar machine, a device of substantial commercial value. Also, a careful study of the back torque (from one of the two external circuits) might reveal a non-zero net torque (i.e. the sum of the torque on the disc and the torque on the external circuit). This could cause a mis-match of the mechanical input power and the electrical output power, meaning that power would either be lost to or gained from an external source. This could represent a new method of energy production, depending on the exact nature of the external source.

If a linear version of such a machine were built, the non-zero net torque might be replaced by a non-zero net thrust, which would be useful for a reactionless space drive. A thruster that did not depend on reaction caused by ejection of mass would greatly extend the range of existing spacecraft, perhaps even making interstellar travel feasible.

For these, and other, reasons, a replication of A.G. Kelly's results would surely be a worthwhile endeavor.

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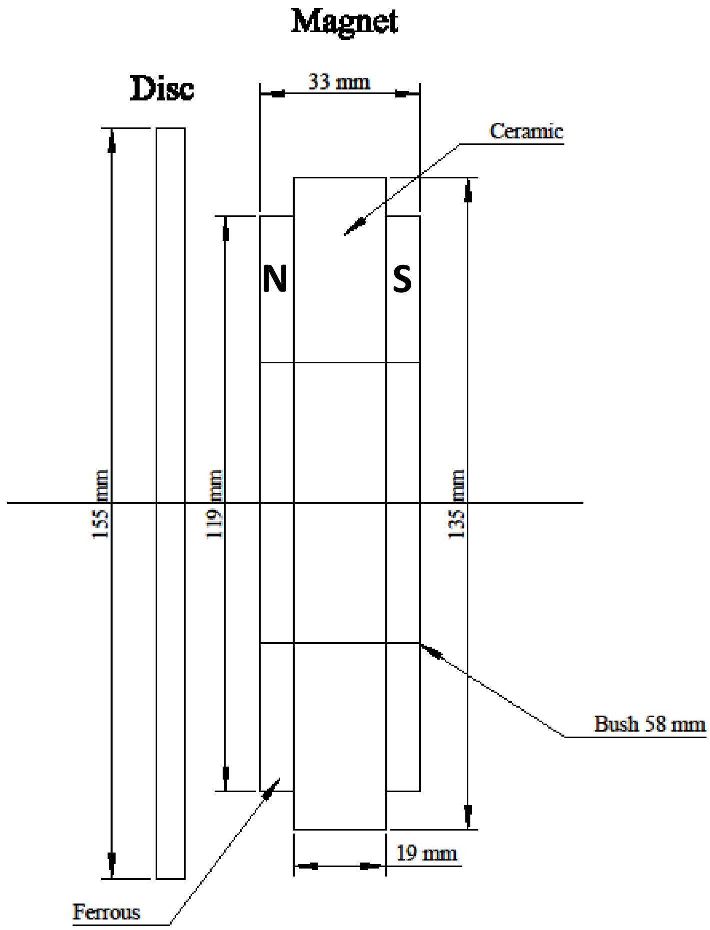
[1] " Faraday's Final Riddle; Does the Field Rotate with a Magnet?" , A.G. Kelly, PhD CEng FASME FIMechE Monographs 5 & 6 of the Institution of Engineers of Ireland, published November 1998. [ISBN No's 1 898012 37 3 & 1 898012 42 3]

APPARATUS

The apparatus comprises a 12.7 mm shaft, on which is mounted an aluminum disc, which forms the conductor. On the other end of the shaft is mounted a magnet. The magnet and the disc could be rotated in unison, or the magnet could be un-clamped from the shaft and clamped instead to the base of the apparatus so that it remains stationary. A voltmeter is connected between a carbon brush rubbing on the rim and the bronze bearing in which the shaft rotates. The distance between the disc and the magnet can be adjusted, and was set to 35 mm for this experiment. The magnet has a head-and-shoulders shape and is 33 mm in length; the central portion (19 mm long in the North-South direction) is of ceramic material, and the two side portions (each 6.4 mm long) of mild steel. The diameter of the ceramic portion is 135 mm, and that of the ferrous parts is 119mm. The disc is 155 mm diameter and 6.4 mm wide. There is an annular hole through the magnet, of diameter 58mm. Bronze bearings in the bushing allow the shaft to rotate inside the magnet assembly when stationary, and a clamp collar attaches it to the shaft when co-rotating with the disc.

The voltage on the brush can be measured using either an analog HP 419A DC Null Voltmeter, which can resolve 0.1 microvolts, or a digital Beckman Industrial 4410 Digital Voltmeter, which can resolve 10 microvolts. An optional 20 ohm resistor can be connected in parallel with the voltmeter to simulate the impedance of the galvanometer used by A.G. Kelly. The analog meter was found to be essential for troubleshooting problems of eccentricity and vibration, where it was necessary to observe the dynamics of the situation. The brush was taken from a small DC motor, and was a carbon brush mounted on a phosphor bronze spring. The brush force was a few grams.



Magnet Apparatus

METHOD

A number of problems were encountered with the apparatus as designed by A.G. Kelly. Many of these stemmed from the use of aluminum as a slip ring on the outside of the rotor. No separate slip ring was used, Kelly simply pressed the carbon brush against the outer edge of the aluminum disc. Usually slip rings are made from copper, brass, or steel, but for this experiment aluminum was used instead so as to reproduce Kelly's experiment as faithfully as possible. In the same spirit, two mild steel pole pieces were used, even though they do not appreciably affect the magnetic field. They do serve to make the magnet electrically conducting, but since there was never any variation in the magnetic field this probably did not affect anything.

The use of aluminum for the rotor led to the formation of a layer of thin and hard oxide on the surface, so that the graphite brush had difficulty making contact with the rotor. Because the voltages involved were only a few millivolts, no electrical breakdown of this oxide film was possible. Also, Kelly used a galvanometer with an impedance of only 20 ohms, so that a slight oxide film made a big difference to the reading. This experimenter initially used a voltmeter in parallel with a 20 ohm resistor to simulate a galvanometer, but it was not possible to get reproducible results. Eventually, the 20 ohm resistor was abandoned and either a digital voltmeter or an old-school analog DC null voltmeter set to a full scale deflection of 10 millivolts was used. The analog meter revealed that the brush was hyper-sensitive to any eccentricity in the rotor, so the entire rotor assembly had to be re-machined. It was mounted in a lathe fully assembled and the periphery machined slightly to give a concentricity tolerance of around +-20 microns. It was also noted that vibration was more of a problem when the heavy magnet assembly was rotating than it was with a fixed magnet, which also affected reproducibility. Another difficulty concerned the connection of the wire to the brush. As the wire was moved this tended to move the brush itself very slightly, which made a substantial difference to the voltage measured across the 20 ohm resistor. This was particularly true when higher levels of vibration were present from the rotating magnet. For these reasons, the following modifications were made to the apparatus:-

1) The 20 ohm resistor was removed, leaving a 10 Megohm input impedance for the voltmeter.

2) Originally one end of the drive shaft had simply been chucked in the electric drill, but the chuck was not sufficiently concentric for the requirements of the experiment. Accordingly, two self-aligning journal bearings were used for the shaft (stainless steel on bronze, lubricated with light spindle oil) and the shaft was driven from the electric drill using a flexible shaft coupling.

3) The rotor was re-machined in a fully assembled state to give good concentricity.

4) The graphite brush was solidly mounted and well isolated from mechanical stress as the connecting wire was moved.

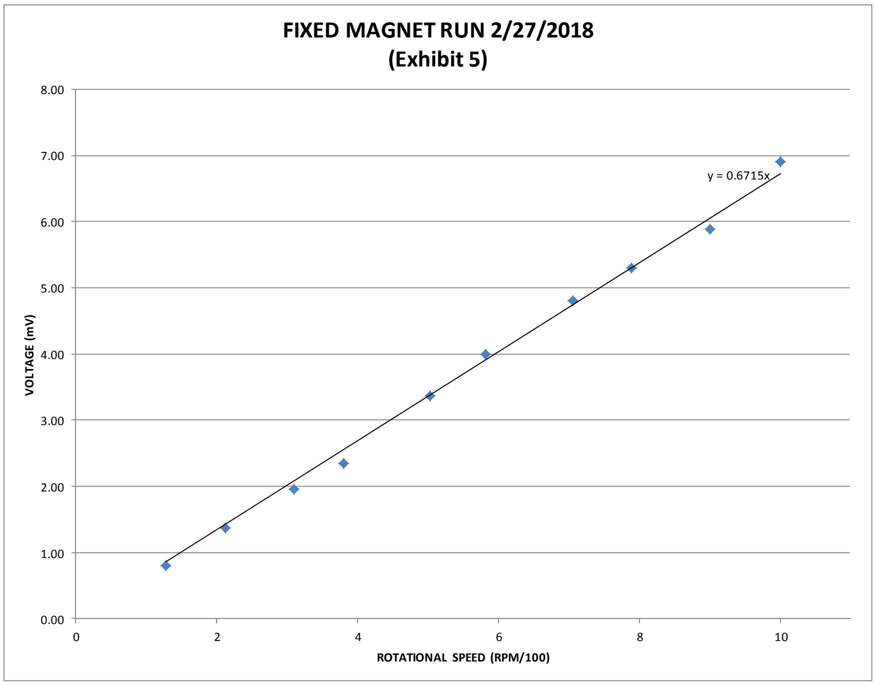
Once these modifications had been completed, graphs were plotted of output voltage versus shaft speed for a number of different speeds from zero to 1000 RPM. This was always done in the direction of increasing speed, since a higher speed tended to affect the oxide layer, which would cause a different reading when the speed was reduced again. Speed runs were done both with a fixed magnet and a co-rotating magnet. The speed was limited to 1000 RPM by the mechanical strength of the ceramic disc magnet.

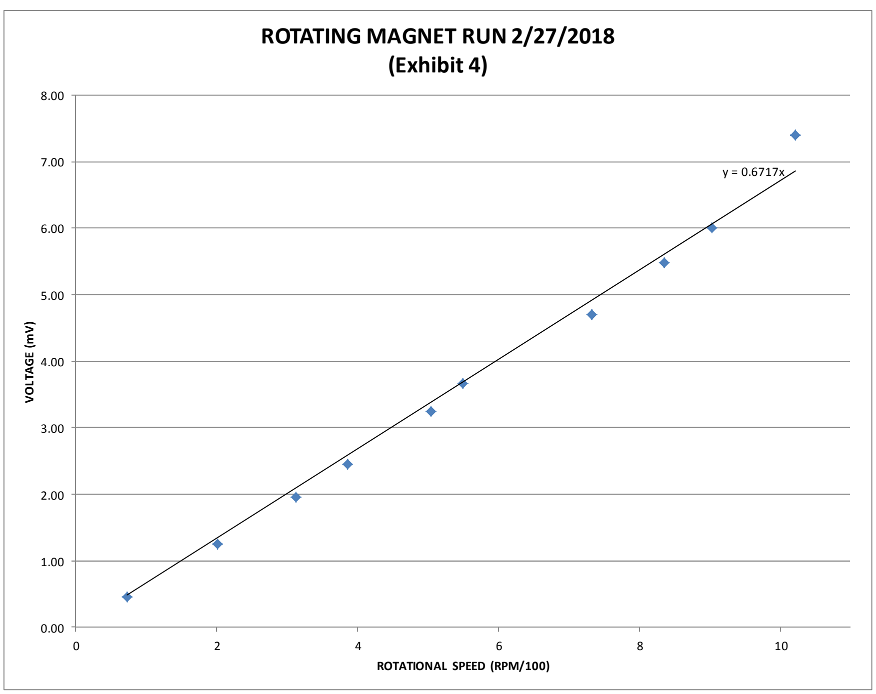
Wire routing experiments were performed with both a fixed magnet and a co-rotating magnet. The wire from the brush was routed either directly to the voltmeter, using the zig-zag route described by Kelly, or any other routing that the experimenter could think of. The analog voltmeter showed the expected transient as the wire was moved through the magnetic field, but the voltage always settled down to the same value for a given RPM no matter what route was taken, whether the magnet was co-rotating or not.

A video of the experiment was taken, and posted on YouTube. The name A.G. Kelly was included as a keyword so as to facilitate location of this video.

RESULTS

The two speed runs, with a fixed magnet and a co-rotating magnet, are plotted below. A linear regression fit (through the origin) was performed on each set of data in order to determine the slope of the line. This slope gives the performance of the generator in terms of volts per RPM.





Note the slightly high reading at 1000 RPM. This was likely caused by a partial breakdown of the oxide layer at high brush speed, and was observed on both runs.

As previously mentioned, the routing of the wire from the brush to the voltmeter was varied in an attempt to replicate the variation in voltage observed by Kelly. However, no such variation was produced no matter what route was used or whether the magnet was co-rotating or fixed. Note that when Michael Faraday performed this experiment in 1851 he did not report any such effect, and also that Maxwell's Equations do not predict any such effect.

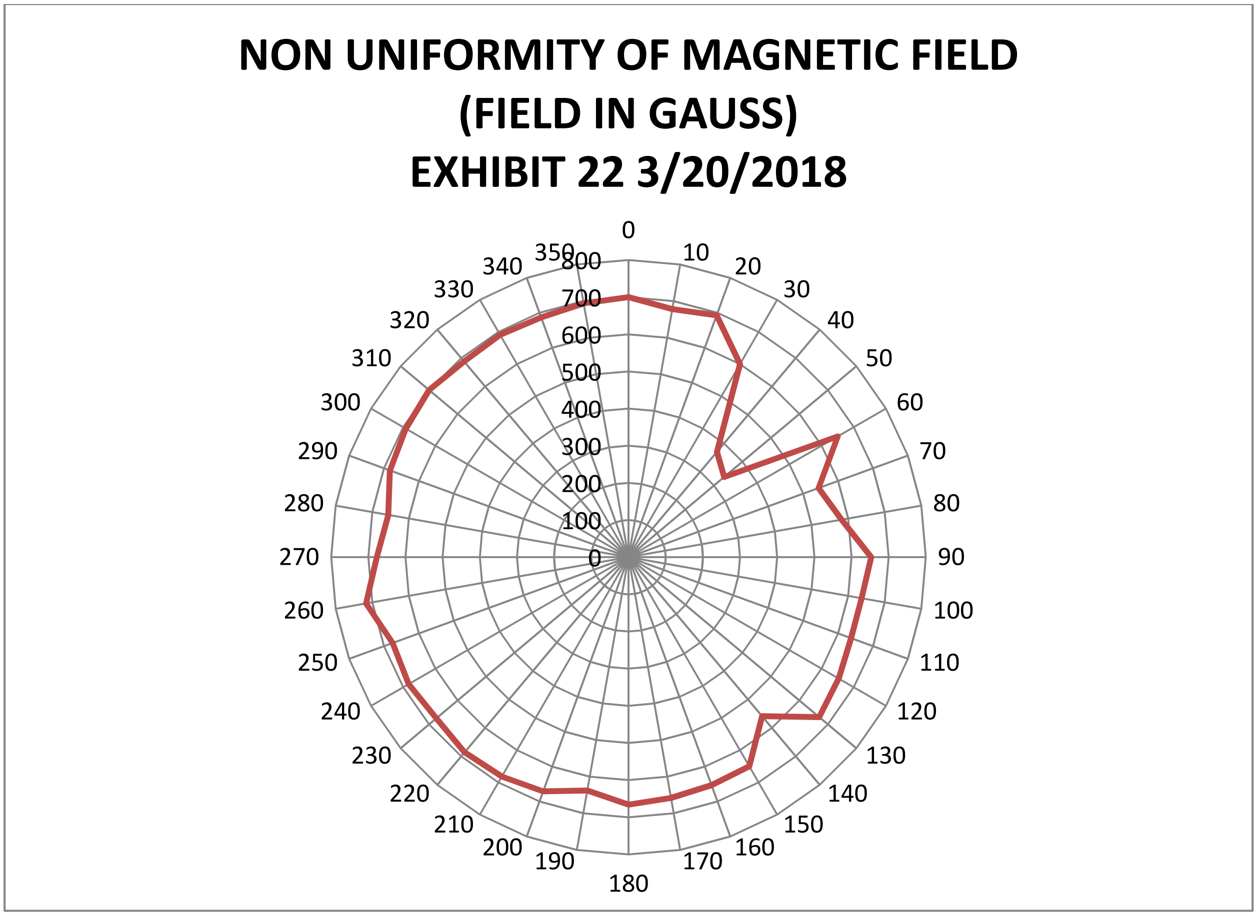
CONCLUSIONS

The voltage performance of the generator was found to be the same within 1% whether the magnet was fixed or co-rotating. This is in accordance with the predictions made by Maxwell's Equations, and also in accordance with the experimental results of Michael Faraday. However, it does NOT agree with the experimental results of A.G. Kelly, who found a substantial difference between the two depending on the way in which he routed the wire. He could even make the generated voltage zero within the tolerance of his galvanometer, simply by using a zig-zag routing of the wire from the brush to the galvanometer.

In short, this experiment has verified the Faraday Paradox (that rotating the magnet makes no difference), but it has failed to replicate the results of A.G. Kelly. The only difference between the experiments is that, while Kelly used a galvanometer with an input impedance of only 20 ohms, this experimenter was not able to get reproducible results using such an impedance (because of the improper rotor material also used, both by Kelly and this experimenter) and so was forced to use an ordinary voltmeter, with the standard input impedance of 10 Megohms that is generally used today.

APPENDIX I

This appendix was added on 3/21/2018, after a private communication with George Hathaway. He was concerned about the homogeneity of the ceramic magnet. Accordingly, the axial field was measured on the outer edge of the magnet closest to the disc using a Hall Effect magnetometer. The measured field is shown below:



As may be seen, the axial magnetic field varied by more than a factor of 2:1 as the magnet rotated. This acted as a spinning bar magnet, inducing a large AC signal in the connecting wires. The value of this signal varied with the routing of the wires.

While the DVM used was able to tolerate a large superimposed AC signal, the “galvanometer” used by Kelly most likely was not. Hence his anomalous readings could have been an artifact caused by the inhomogeneity of the magnetic field. This would have accounted for the observed dependence on the routing of the wires, and also on his observed requirement that the magnet be rotating. This experimenter did not observe any anomalous readings because the modern digital voltmeter used (a Beckman Industrial 4410) was not sensitive to a superimposed AC signal.