Using Ferrofluid as a Field Magnet: a Ferrofluid Electromagnetic Generator.

David Morrow
Physics Department, The College of Wooster, Wooster, Ohio 44691, USA
(Dated: May 16, 2018)

This article discusses an investigation into the use of a ferrofluid as a field magnet for an electromagnetic generator. A small generator was constructed using pre-made materials including a glass vial, ferrofluid and magnet wire. Using a current preamplifier and an oscilloscope voltage was record while the generator was shaken. The maximum RMS voltage recorded was 4.19 mV. This finding agrees with those of similar experiments. This RMS voltage was found at 8.97 Hz. There was found to be a direct correlation between RMS voltage and frequency.

I. INTRODUCTION

A ferrofluid is essentially a liquid that can be magnetized using a magnetic field. More correctly a ferrofluid is created by suspending nano-sized particles in a carrier fluid. The particles in modern ferrofluids are coated in surfactant. Each of these particles are permanent magnets. The surfactant prevents the magnetic particles from congregating and falling out of suspension While it is in a magnetized state the ferrofluid exhibit the properties of a magnet. Interestingly, while magnetized the ferrofluid still exhibits the properties of a liquid. Ferrofluid was first synthesized in 1963. Originally, intended to be uses as rocket fuel, the magnetic properties allowed the ferrofluid to be oriented in zero gravity[1]. However, the combination of magnetism and liquid state makes feroflid useful in many different applications including as a seal for hard drives, in stretchy inductors, as a thermal conductor for loud speakers, and in electromagnetic generators [2, 3].

In terms of generating electricity ferrofluid can be applied in two ways. Ferrofluid can be used to lubricate the field magnet of an electromagnetic generator or it can be used as the field magnet itself[4–6]. As a lubricant, ferrofluid is useful for the same reason it was used in rocket fuel, it allows a liquid to be positioned. The ferrofluid lubricant will always be surrounding the field magnet. While use as a lubricant is effective, the liquid properties of ferrofluid also lend themselves to use as a field magnet. Liquids are more sensitive to vibrations and perturbations. This susceptibility may make ferrofluid a better field magnet then a solid alternative.

To evaluate how effective ferrofluid is as a field magnet, a generator will be made consisting of a bottle, a quantity of ferrofluid, magnet wire and permanent magnets used to magnetize the ferrofluid. The generator will then be tested by shaking and monitoring the output of the generator.

FIG. 1: The ferrofluid electromagnetic generator constructed. Inside the bottle is 15 ml of ferrofluid. Around the outside is 500 turns of magnet wire.

II. THEORY

A. Induction

The generator seen in Fig. 1 relies on the same basic concept as other electromagnetic generators. Changes in the magnetic flux create current in a pick up coil. Magnetic flux Φ is defined to be

$$\Phi = \vec{B} \cdot \vec{A}, \tag{1}$$

where, B is the magnetic field, and A is the area of interest. The dot product can also be written as $\Phi = BA\cos(\theta)$ where θ is the angle between the vector normal to plane A and the vector B. For an equation that results in emf $\mathcal{E}$, Faraday's law is needed. A simple form of Faraday's law is written as

$$\mathcal{E} = -\frac{d\Phi}{dt}. \tag{2}$$

Using Farday's Law and the definition of magnetic flux an equation for the emf can be written as [7].

$$\mathcal{E} = \frac{\delta B}{\delta t} A \cos\theta - \frac{\delta A}{\delta t} B \cos\theta - AB\cos\theta \frac{\delta\theta}{\delta t}). \quad (3)$$

This equation can be simplified. Firstly, A will not change because the area of interest that is the pick up coil will not change. (It can also be assumed that the ferrofluid will give out a constant magnetic field). This means the only cause of emf will be changes in θ. Once simplified an additional term needs to be added to allow the equation to be applied to the generator. A term needs to be added to represent the number of turns in the coil. This term N is the number of turns and is a multiplier.

$$\mathcal{E} = -NAB\cos\theta \frac{\delta\theta}{\delta t} \quad (4)$$

B. Ferrofluid

As discussed briefly above ferrofluid is a liquid that exhibits magnetism in a magnetic field. The magnetism of the ferrofluid comes from the magnet nanoparticle that are in suspension in the fluid. While not in a magnetic field the magnetic nanoparticles assume random orientation. The random orientation leads the fluid to not exhibit any magnetic properties. However, when a magnetic field is introduced each of the nanoparticles aligns with the magnetic fields. The alignment of these particle then causes the liquid to act as a magnet. Fig. 2 is a visual representation of the particle in ferrofluid inside and outside a magnetic field. Ferrofluid does not lose its liquid properties while magnetized. The ferrofluid is able to maintain its liquid state because the nanoparticles are able to stay suspended due to the surfactant that they are coated in [2, 8].

C. Induction in Ferrofluid

The main way that the ferrofluid creates magnetic flux is via a sloshing motion. Sloshing is the irregular motion of a liquid in a container. Sloshing occurs when a liquid moves in any container. A good example of sloshing is how waves in a pool splash on the side of the pool. However, sloshing occurs in all containers. Fig. 3 shows a visual representation of sloshing with in the generator. Sloshing motion is affected by a number of factors including the size and shape of the container, the viscosity of the liquid, and the volume of liquid. The sloshing motion is the main cause of magnetic flux as it causes a mass movement of the nanoparticles. There is some magnetic flux created by the motion of particles in the ferrofluid. However, this magnetic flux is negligible. As the motion of a single particle creates negligible magnetic flux. Because small perturbations can cause a sloshing motion sloshing requires little energy compared to that required to move a solid magnet [6, 8–10].

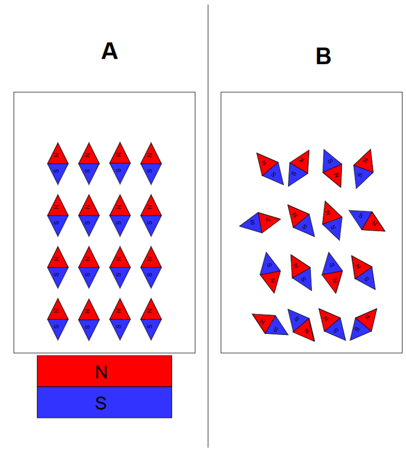

FIG. 2: Side A shows a visual representation of the alignment of the nanoparticles in a magnetic field. Side B shows the random alignment of the nanoparticles when not in a magnetic field. This visual is inspired by images from source [5].

Another component of sloshing is natural frequencies. Much like other media, ferrofluid has natural frequencies. A natural frequency is the frequency a medium would vibrate at when unstimulated. When vibrated at a natural frequency the amplitude will increase. When a ferrofluid is vibrated at one of its natural frequencies it creates larger surface waves[8–10]. A more complete treatment of sloshing and ferrofluid dynamics can be found in either of the two Odenbach books [2, 8].

A handful of other studies have looked into the use of ferrofluid as field magnet [5, 6, 9]. These studies focused on a small range of frequencies at small amplitudes. All of the studies find that the relationship between frequency and voltage is not strictly linear. Much of the data features sections of approximately linear data.

Looking at Eq (4) one would expect that larger frequencies would create a larger emf. The finds of other inquires disagree with this predictions. This is because the other studies are using small amplitude motions and relying mainly on the surface waves created. At larger amplitudes a strictly linear relationship between frequency and voltage is expected. This relationship is expected because at higher frequencies the change in magnetic flux will be greater from instant to instant.

III. EXPERIMENTAL SETUP

The experiment setup consists of the generator and the measurement equipment. The generator was custom built for this experiment. The generator's dimensions were chosen by taking in to account the measurements in a number of articles [5, 6, 9]. The body of the generator was a McMaster-Carr style D glass vial. The vial was chosen as the body because its shape and size were

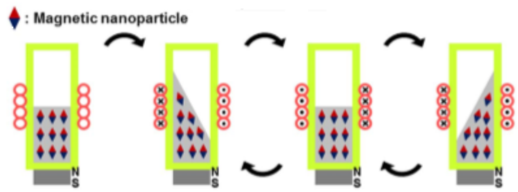

FIG. 3: A diagram of the internal sloshing motion of the generator as well as a representation of the effect on the induction coil. Taken from source [5].

FIG. 4: The orientation of the generator. The generator was moved from one side of the board to the other.

similar to the generators discussed in articles addressing ferrofluid electromagnetic generators. The vial also had very little lead time compared to manufacturing a vessel. Within the vial was placed 15 ml of ferrofluid. Ferrotec EFH 1 ferrofluid was the chosen ferrofluid. This ferrofluid was chosen because it was cost effective and easily available. Around the outside of the vial is a pick up coil. This pick up coil was made of 500 turns of magnet wire. At turn 297 of the coil there is a piece of solder. This irregularity likely represents two pieces of wire that were joined. An image of the generator can be seen in Fig. 1.

The measurement equipment used consists of a Stanford Research Systems model SR570 current preamplifier and a Tektronix TDS 2024B oscilloscope. The signal from the generator was first sent through the current preamplifier. The preamplifier amplified the signal by 10 μA/V. The signal was then read by the oscilloscope. Once the signal reading on the oscilloscopes became regular the reading was paused and saved to a flash drive. The data was taken from the flash drive and imported in to Igor Pro for analysis.

The generator was shaken by hand. While not ideal, the original shaking mechanism used an electric motor that interfered with the magnetic field of the ferrofluid. The frequency was regulated by looking at the oscilloscope and approximating when the signal was regular. The amplitude of the motion was 7 cm. The amplitude was measured using a piece of wood. The cap of the generator was moved to align with the top on the upstroke and the base of the generator was moved to the bottom of the board on the down stroke. While being shaken the generator was aligned so that the coils were perpendicular to the ground and the direction of motion. The orientation of the generator and the direction of motion are displayed in Fig. 4. The magnets were placed parallel to the coils.

IV. RESULTS

The data files were imported to Igor Pro. In Igor Pro, the voltage was plotted against time to create a graph of the signal. An example of one of these graphs can be seen in Fig. 5. From the graph, frequency was determined by counting the peaks and dividing by time between the first peak and the last. Noticeably after every peak there was a secondary peak. These secondary peaks come from the sloshing motion of the ferrofluid and were not counted when calculating the frequency. This less then ideal method of calculating the frequency had to be used because it was impossible to be certain of the frequency the generator was moved at because it was done by hand.

From the graph of the signal the RMS (root mean squared) voltage was also found. The RMS voltage was found using Igor pro's wave statistics tool. Frequency and RMS voltage were found for 18 runs. The frequencies ranged from $0-9$ Hz. Voltage tended to be higher for higher frequencies. Looking at Fig. 5 and Fig. 6 there is one very evident difference. The distance between peaks is larger in Fig. 6 this show that the frequency in Fig. 5 is higher then that of Fig. 6. Another difference can be seen in the height of the peaks. The peaks are higher in Fig. 5, this is also related to the frequency as a higher frequency means the ferrofluid itself is moving faster. The faster movement result in a larger change of flux from moment to moment.

A graph of the RMS voltage plotted against frequency can be seen in Fig. 7. A maximum RMS voltage of 4.19 mV was achieved at 9 Hz. It is likely even higher RMS voltages can be achieved at higher frequencies. These RMS voltages are comparable to other studies of similar generators [5, 6, 9].

Noticeably in Fig (7) some recorded RMS voltage are lower despite being at a higher frequency. This suggests that the relationship between frequency and RMS voltage might not be strictly linear. This is confirmed by literature [9]. Mentioned above, a number of studies [5, 6, 9] have investigated similar generators at small amplitudes. It was universally found that the relationship between frequency and voltage was not linear.However, these findings are not directly comparable to the data in this study. During the shaking process it was noted that the majority of the ferrofluid was mobilized. This was seen because the ferrofluid coated the inside of the generator. This case varies greatly from the cases treated in the literature where the majority of flux was created from

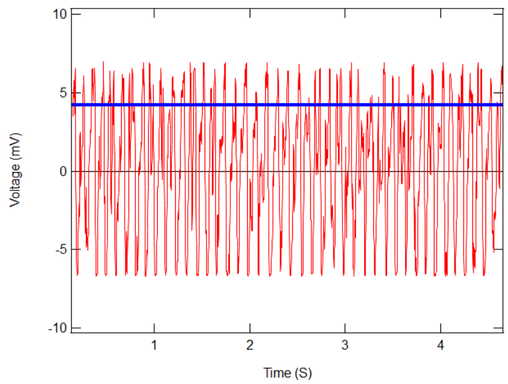

FIG. 5: A graph of the voltage signal recorded by the oscilloscope presented using Igor pro. The blue line represents the RMS (root mean squared) voltage. This run is the one that created the largest RMS voltage of 4.19 mV.

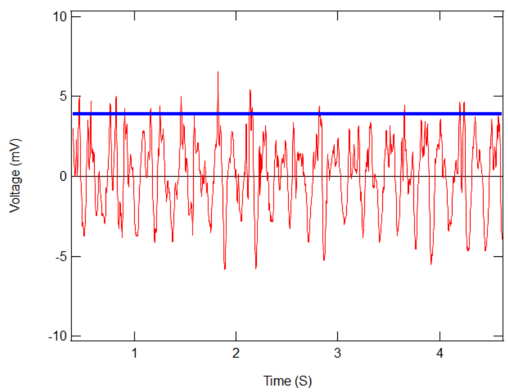

FIG. 6: A graph of the voltage signal recorded by the oscilloscope presented using Igor pro. The blue line represents the RMS voltage. This run created a RMS voltage of 3.87 mV.

surface waves. As mentioned in Theory section discussing sloshing, it is possible to shake the generator at a natural frequency. Shaking at a natural frequency will cause greater surface wave and thus greater change in the magnetic flux. Unfortunately, it is beyond the scope of this paper to predict and test such frequencies. However, it is possible that some of the tested frequencies were closer to a natural frequency. This would explain why some lower frequencies created higher RMS voltages. However, the effect of shaking at a natural frequency would be quite large so it is unlikely this the cause.

Another possible source of this inconsistency might be the motion of the generator not being uniform. It is possible that the upstroke could have been faster then the down stroke or the speed of the motion changed through out. This could create the appearance of a regular frequency while creating a larger RMS voltage. This is likely a problem in at least one run as the generator was shaken by hand.

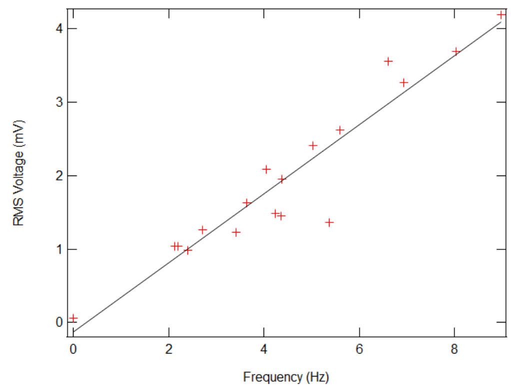

FIG. 7: Graph of the RMS voltage plotted against the frequency that produced the voltage. Each point represents a single run. The line of best fit has the equation $V = (0.47 \pm 0.04)F - (0.1 \pm 0.2)$. where F is the frequency and V is the voltage in mV. This line is not a good predictor of the RMS voltage. It serves the purpose of illustrating the upward trend of the data.

V. CONCLUSION

As seen in Fig (7) there is a positive relationship between frequency and RMS voltage. The max achieved RMS voltage was 4.19 mV. This confirms that ferrofluid is a viable field magnet for a generator. While there is still more research that needs to be done, the max RMS does agree with values found in similar experiments [5, 6, 9].

First, a better way of shaking the generator needs to be found. As briefly mentioned above an electric motor was originally used. However, the magnetic field created by the motor interfered with the generator. Furthermore, if the generator is intended to be used to generate power using an electric motor would defeat the purpose. For further research one could use a shielded motor. With a motor the frequency of the motion could be controlled. Other ferrofluids also should be tested. Different ferrofluid will have different field strengths and viscousities. These different properties will affect the magnetic flux created from motion.

Further theoretical work also needs to be done. A theoretical generator could be designed that would be more efficient. The efficiency of this generator could be increased by creating a container that has a natural frequency at a desired frequency. This task has been undertaken before [9]. However, the approach was experimental. The choice to use experimental data to find a natural frequency was done due to the complicated nature of solving equations in ferrofluid dynamics. However, if a value was found computationally it would help research in to ferrofluid generators. Additionally, generators of different sizes should be investigated. All of the current research done has used similar sized generators [5, 6, 9]. It is suggested that the output of the generator will scale. However, there is not current data on a larger generator.

Sources of energy also need to be investigated. The generator needs to be shaken or vibrated to create a current. Sources suggested in the literature include seismic energy, human motion, and vibration of machinery[5]. The effectiveness of the generator to harvest these sources needs to be investigated. There has been a study involving ferrofluid and human motion. However, it was a generator that used a permanent magnet lubricated by ferrofluid [4].

Acknowledgements

I would like to thank Tim Siegenthaler for the construction of the shaker table, The College of Wooster Physics Department for providing equipment and funding for this paper, and Dr. Susan Lehman of the College of Wooster Physics Department for her guidance and help with the paper.

[1] P. S. Stephen, *Low viscosity magnetic fluid obtained by the colloidal suspension of magnetic particles* (1965).

[2] S. Odenbach, *Colloidal Magnetic Fluids Basics, Development and Application of Ferrofluids* (Springer Verlag, Berlin, 2009).

[3] N. Lazarus and C. Meyer, Journal of Physics: Conference Series **660**, 7 (2015).

[4] S. Wang and D. Li, Journal of the Korean Physical Society **67**, 818 (2015).

[5] M.-L. Seol, S.-B. Jeon, J.-W. Han, and Y.-K. Choi, Nano Energy **31**, 233 (2017).

[6] S. Alazemi, A. Bibo, and M. Daqaq, The European Physical Journal Special Topics **224**, 2993 (2015).

[7] D. Griffiths, *Introduction to Electrodynamics* (Pearson India Education Services, Noida, India, 2015), 4th ed.

[8] S. Odenbach, *Ferrofluids: Magnetically Controllable Fluids and Their Applications* (Springer Berlin Heidelberg, Berlin, 2003).

[9] A. Bibo, R. Masana, A. King, G. Li, and M. Daqaq, Physics Letters A **376**, 2163 (2012).

[10] S. Alazmi, Y. Xu, and M. Daqaq, Physics of Fluids **28**, 77 (2016).