

Energy harvesting via ferrofluidic induction

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ABSTRACT

A series of experiments were conducted to investigate and characterize the concept of ferrofluidic induction - a process for generating electrical power via cyclic oscillation of ferrofluid (iron-based nanofluid) through a solenoid. Experimental parameters include: number of bias magnets, magnet spacing, solenoid core, fluid pulse frequency and ferrofluid-particle diameter. A peristaltic pump was used to cyclically drive two aqueous ferrofluids, consisting of 7-10 nm iron-oxide particles and commercially-available hydroxyl-coated magnetic beads (~800 nm), respectively. The solutions were pulsed at 3, 6, and 10 Hz through 3.2 mm internal diameter Tygon tubing. A 1000 turn copper-wire solenoid was placed around the tube 45 cm away from the pump. The experimental results indicate that the ferrofluid is capable of inducing a maximum electric potential of approximately $\pm 20 \mu\text{V}$ across the solenoid during its cyclic passage. As the frequency of the pulsating flow increased, the ferro-nanoparticle diameter increased, or the bias magnet separation decreased, the induced voltage increased. The type of solenoid core material (copper or plastic) did not have a discernible effect on induction. These results demonstrate the feasibility of ferrofluidic induction and provide insight into its dependence on fluid/flow parameters. Such fluidic/magneto-coupling can be exploited for energy harvesting and/or conversion system design for a variety of applications.

Keywords: Energy harvesting, ferrofluid, nanofluid, electromagnetic induction, pulsating flow

1. INTRODUCTION

1.1. Ferrofluid

Colloidal suspensions composed of magnetic particles and a liquid carrier—either organic or aqueous solvents—are commonly referred to ferrofluids. By using surfactants or surface stabilizers, flocculation and/or aggregation of magnetic particles in these types of fluids significantly decreases. The most common magnetic material used in ferrofluids is magnetite, Fe_3O_4 , with sizes that can range between 7-15 nm for single-core particles for stabilized suspensions.¹ Ferrofluid is employed in various applications, such as in biomedical research, microfluidic devices, bioreactors, the detection of viruses and toxins, and many other areas.² For the purpose of energy and electronics, ferrofluids are attractive materials found in motors, generators, acoustics, and ferrofluidic induction. In this particular study, ferrofluidic induction is investigated by using a commercially-available and an in-house synthesized ferrofluid, respectively, as described in the experimental section.

1.2. Harvesting

Sansom et al. performed an experimental study into using commercially-available ferrofluids for waste heat removal and energy harvesting applications.³ In this study, ferrofluid ($\text{Fe}_3\text{O}_4 + \text{H}_2\text{O}$) was actively pumped within a tubular structure (10 mm ID) that was placed adjacently to a copper coil (i.e. inductor) with the intention of producing an electromotive force (EMF) across the inductor. Neodymium magnets were placed near the coil/tube assembly to temporarily magnetize the fluid in the region of the coil. A permanent external field was necessary since the individual magnetic domains of the nanoparticles only remain aligned while subjected to a magnetic field. Alignment of the particle magnetic domains ensures more effective induction in the harvesting/coil region. It was observed that relative to continuous flow, pulsating flow doubled the induced voltage (for a maximum of 3 mV). No mention was made of filtering out high frequency background noise typically inherent to voltage measurements.

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Chen et al.⁴ performed a fundamental investigation into using ferrofluids for inducing an EMF in a copper coil. A Helmholtz coil (two concentric solenoid electromagnets) was utilized to produce a uniform, static magnetic field through two coaxial 1500 turn copper solenoids (the axis of the coils being parallel with the ground). Using a Gaussmeter, the undisturbed field strength at the center of the coils was measured to be 6,127 A/m. A programmable motor was used to vertically raise 1, 2, or 4 mL of commercially-available, oil-based ferrofluid (10 nm Fe₃O₄ particles at 7.8% volume concentration) at a constant speed of 0.02, 0.04, or 0.08 m/s between the solenoids. The length of the cylindrical ferrofluid volume was varied (from 6.3 to 16.56 mm). After data collection, a Fast Fourier Transform was used to filter high frequency noise. Depending on the parameter combination, a 0.1-0.5 mV EMF was induced.

Bibo et al.⁵ experimentally generated a time-varying voltage signal across a solenoid by winding a 1000 turn coil around a ferrofluid-filled (Fe₃O₄ particles, concentration of 15% per volume in light hydrocarbon oil, total fluid density of 1.21 g/cm³), 44 mL cylinder (32mm dia, 55mm tall) with bias magnets located above and below the vessel. The vessel and magnets were affixed to a plate that was then agitated at various frequencies (from 3-10 Hz) to shake the ferrofluid. Results demonstrated that higher voltages could be generated when using stronger bias fields; accomplished by decreasing the distance between the magnets. Also, higher accelerations of the vessel produced higher voltages.

Although some work has been performed in demonstrating the use of ferrofluid for induction, there have not been many, if any, parametric studies on this topic. Hence, this study explores key design parameters affecting ferrofluidic induction, including: number of bias magnets, magnet spacing, solenoid core, fluid pulse frequency and ferrofluid-particle diameter.

2. EXPERIMENTAL DESIGN

2.1. Electromagnetic Requirements

As mentioned, the purpose of the bias magnets is to align the magnetic dipole-moments of each nanoparticle. Without this bias field, the moments would tend to be randomly oriented due to thermal and mechanical motion of the particles in the fluid. Provided that the external field is approximately uniform, the moments will only experience a torque aligning them.⁶ With the moments aligned, the magnetic field produced by the collection of nanoparticles is substantially greater in magnitude than without alignment, and thus, provides a greater flux through the solenoid enhancing the extracted EMF.

2.2. Ferrofluid Characterization

The commercially-available ferrofluid consisted of magnetic beads with hydroxyl surface-functionalized groups, 800 nm in size, a concentration of 10 mg/mL, and water dispersion (Ocean NanoTech). Similarly, the effects of an in-house ferrofluid synthesized using a co-precipitation technique are evaluated.¹ In short, iron (III) and iron (II) chloride solutions were prepared in a 2 M hydrochloric acid solution at a molar ratio of 2:1, respectively. Both iron solutions, mixed independently for five minutes, were then added to an ammonium hydroxide solution (0.7 M) under vigorous stirring. After 30 minutes, a black precipitate was separated with the aid of an external magnet. Several washes included the addition of water, re-suspension of the particles, and magnetic separation. Thus, these techniques guaranteed efficient salts removal and particle separation. Lastly, the electrostatic stabilized colloid was formed by adding perchloric acid (2M) to the black precipitate and by re-suspending in water. Final particle concentration is estimated to be at ~100 mg/mL. For both ferrofluids, the total volume used in all experiments was ~ 10 mL.

2.3. Experimental Setup

The parameters considered for this study were 1) number of bias magnets, 2) magnet spacing, 3) solenoid core, 4) fluid pulse frequency, and 5) fluid. The selections for these parameters are given in Table 1. The tube size was held constant for all tests (3.2 mm ID). In Table 1, Ferrofluid 1 (FF1) is the commercially-available ferrofluid, while Ferrofluid 2 (FF2) is the in-house ferrofluid.

The two 1000-coil solenoids were both made from 0.13 mm copper wire with 12.7 mm ODs. One solenoid consisted of a rigid polypropylene tubing core with copper wire wrapped around its circumference while the other was similar in all attributes sans its core which was copper alloy 122. These two materials were investigated to see if piping material has any significant affect on induced current since a changing magnetic field will induce eddy currents in conductors (such as copper tubing).

Table 1. Parameter space

Parameter	Options
Number of bias magnets	0, 1, 2
Pulse frequency	0 Hz, 3 Hz, 6 Hz, 8 Hz
Fluid	Water, Ferrofluid 1, Ferrofluid 2
Magnet offset	10.2 cm , 15.2 cm , 20.3 cm
Solenoid core	Plastic, Copper

A variable speed Cole Parmer 7553-20 peristaltic pump was used to circulate the test fluid (either deionized water or one of the ferrofluids) through a 3.2 mm ID Tygon tube. The tube was 127 cm long with its ends connected via a small plastic barbed fitting and was secured to a tabletop to prevent movement of the tubing during testing. The solenoids were placed concentrically on the tubing to allow them to be slid into place for their respective tests. During testing, the wires from the utilized solenoid were connected to a 120 Hz, passive, low-pass (LP) filter for signal conditioning, in order to prevent high frequency, ambient signals (e.g. radio, cell phone, etc) from interfering with the data acquisition. The low-pass filter was connected to a data acquisition system (DAQ, National Instruments cDAQ-9178/NI 9205 combination) for voltage sampling/measurement at a rate of 800 Hz. Using Labview software, a 40th order, Butterworth 45 Hz low pass filter was employed to filter any 60 Hz noise from the electrical power supply. The voltage measurements recorded by the DAQ have a resolution of 6 μ V. Figure 1 provides a schematic of the experimental setup.

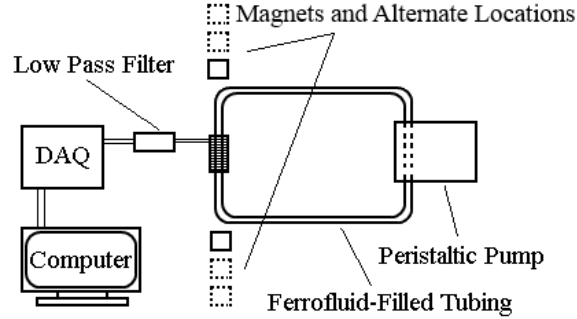


Figure 1. Experimental setup

Stationary, neodymium magnets (16.4 cm³ cubes) were used to temporarily magnetize the liquid-suspended nanoparticles in the region of the solenoid. Tests were performed while using 2, 1 or no bias magnets and the location of the magnets were varied to be 10.2, 15.2 or 20.3 cm (± 1 mm) coaxially from the center of the solenoid being tested. The pumping frequency was varied (0, 3, 6, and 10 Hz all at ± 0.1 Hz) for both solenoids investigated, for one or both bias magnets, at all possible equal offsets (no combinations of different offsets were tested), for both working fluids. Based on the parameter space designed for the current experiment, 168 individual tests were conducted, including tests where no bias magnets were present.

3. RESULTS

3.1. Data Processing

Let $v[n]$ denote the voltage measured across the solenoid at time $n\Delta t$ where $0 \leq n < N$, N is the number of samples recorded, and Δt is the sampling period (if the signal is sampled at frequency f_s , then $\Delta t = 1 / f_s$). Herein, all signals were truncated to a length of $N = 48000$ samples with $f_s = 800$ Hz. Prior to analysis, the voltage signal was shifted to oscillate about zero by subtracting its mean value, i.e. the analysis was conducted using the zero-shifted voltage signal $x[n]$ defined as:

$$x[n] = v[n] - \frac{1}{N} \sum_{m=0}^{N-1} v[m]. \quad (1)$$

The induced voltage measured across the solenoid in this experiment is inherently oscillatory due to the pulsating nature of the fluid flow. Hence, Fourier analysis was used to characterize the amplitude and frequency of oscillations in these voltage signals. Let $X[k]$ denote the discrete Fourier transform of $x[n]$, given by:⁷

$$X[k] = \sum_{n=0}^{N-1} x[n] \exp(-2\pi jkn / N). \quad (2)$$

Then the amplitude spectrum of signal $x[n]$ is:

$$S[k] = \begin{cases} \frac{1}{N} |X[k]|, & k = 0 \text{ or } k = \left\lfloor \frac{N+1}{2} \right\rfloor, \\ \frac{2}{N} |X[k]|, & 0 < k < \left\lfloor \frac{N+1}{2} \right\rfloor \end{cases} \quad (3)$$

where $0 \leq k \leq [N/2]$. Thus, the amplitude spectrum $S[k]$ is the magnitude of the complex-valued coefficient of the sinusoidal Fourier component at frequency $k / (N\Delta t)$. Here, both the maximum value of $S[k]$ and the frequency at which this maximum value occurred were plotted against pump frequency for each test in order to examine the relation between pump frequency and the amplitude/frequency of the induced voltage.

3.2. Aggregated Results

Figure 2-4 show the maximum value of $S[k]$ vs. pump frequency for each combination of working fluid, solenoid core, number of bias magnets, and bias magnet spacing. Note that in order for data to be more clearly presented, the y-axis scale varies for Figs. 2-4.

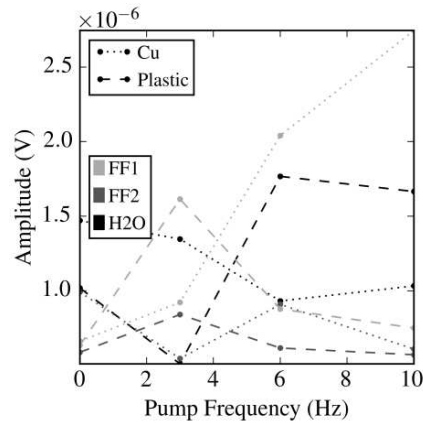


Figure 2. Maximum value of amplitude spectrum vs. pump frequency for tests with no bias magnets.

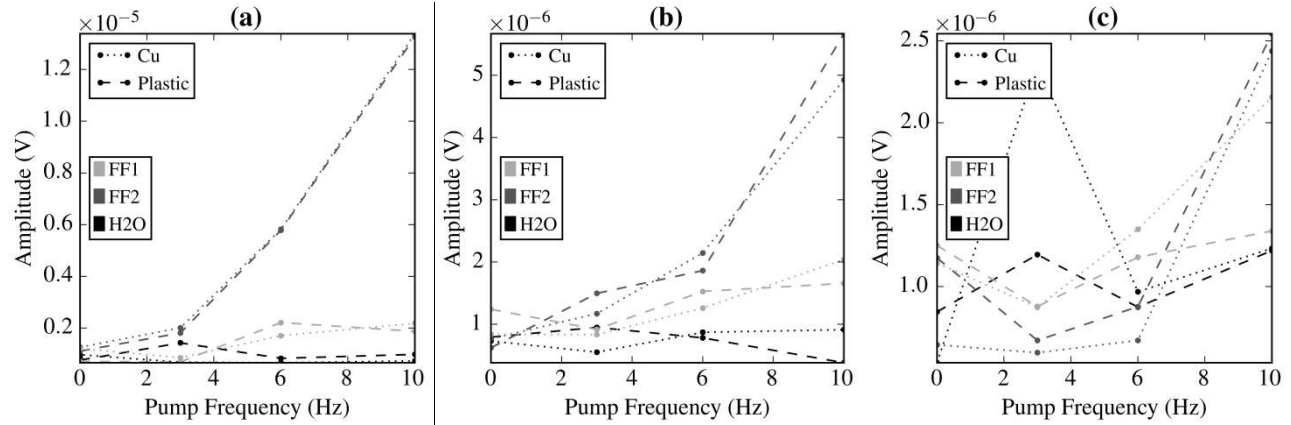


Figure 3. Maximum value of amplitude spectrum vs. pump frequency for tests with one bias magnet. Magnet spacing: (a) 10.2 cm, (b) 15.2 cm, and (c) 20.3 cm.

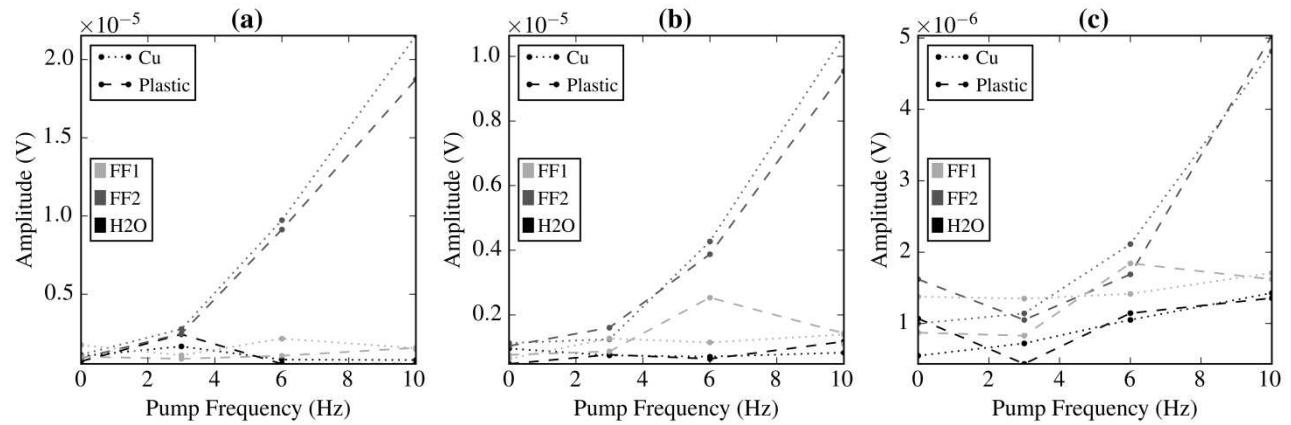


Figure 4. Maximum value of amplitude spectrum vs. pump frequency for tests with two bias magnets. Magnet spacing: (a) 10.2 cm, (b) 15.2 cm, and (c) 20.3 cm.

As can be seen in Figs. 2-3, the voltage generation is maximized with two closely positioned bias magnets. This confirms the findings of Bibo et al. ⁵ in that a stronger bias field yields greater voltage amplitudes. It is observed that the amplitude also increases with increased pump frequency. As expected, there is negligible voltage generation without the presence of bias magnets. It can be concluded that the amplitude of the generated voltage signal is positively influenced by both pump frequency and the strength of the bias field. Furthermore, the more concentrated ferrofluid (FF2: ~100 mg/mL) produced a higher amplitude voltage than the other (FF1: 10 mg/mL). It is also noteworthy that there is no significant difference between voltage generation when copper or plastic shielding is present between the solenoid and the ferrofluid. This suggests that the signal generation can be replicated using copper tubing to transport the ferrofluid; thus allowing for further development and implementation of the technology.

Figure 5-7 provide the frequency of the maximum amplitude spectrum component vs. pump frequency for each combination of working fluid, solenoid core, number of bias magnets, and bias magnet spacing.

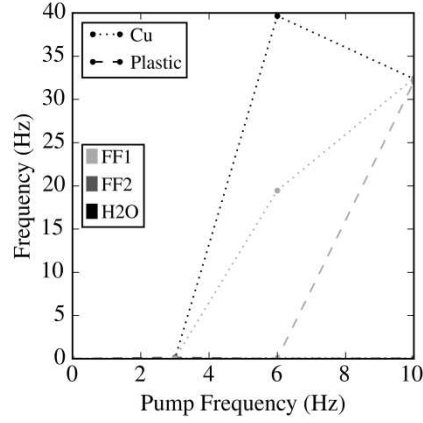


Figure 5. Frequency of maximum amplitude spectrum component vs. pump frequency for tests with no bias magnets.

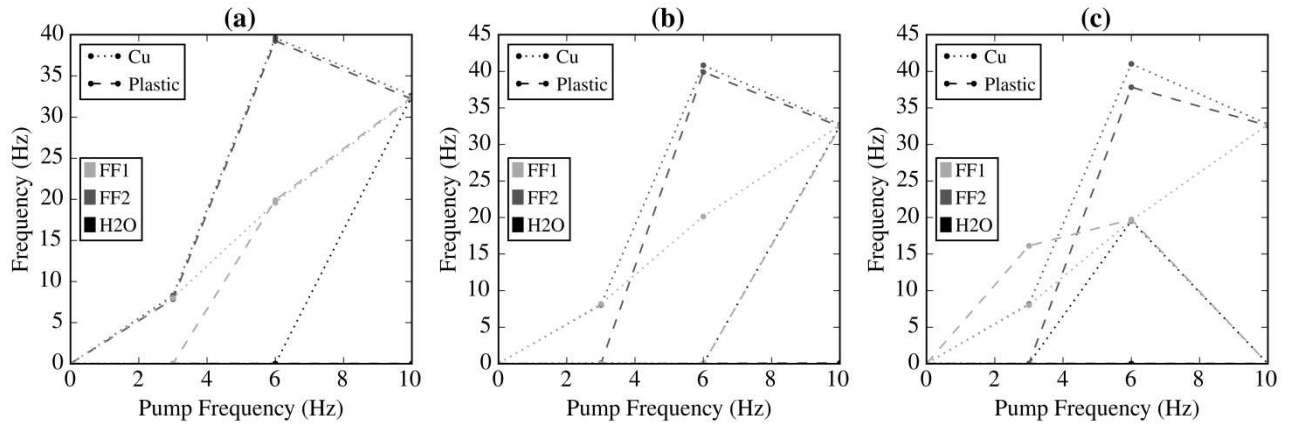


Figure 6. Frequency of maximum amplitude spectrum component vs. pump frequency for tests with one bias magnet. Magnet spacing: (a) 10.2 cm, (b) 15.2 cm, and (c) 20.3 cm.

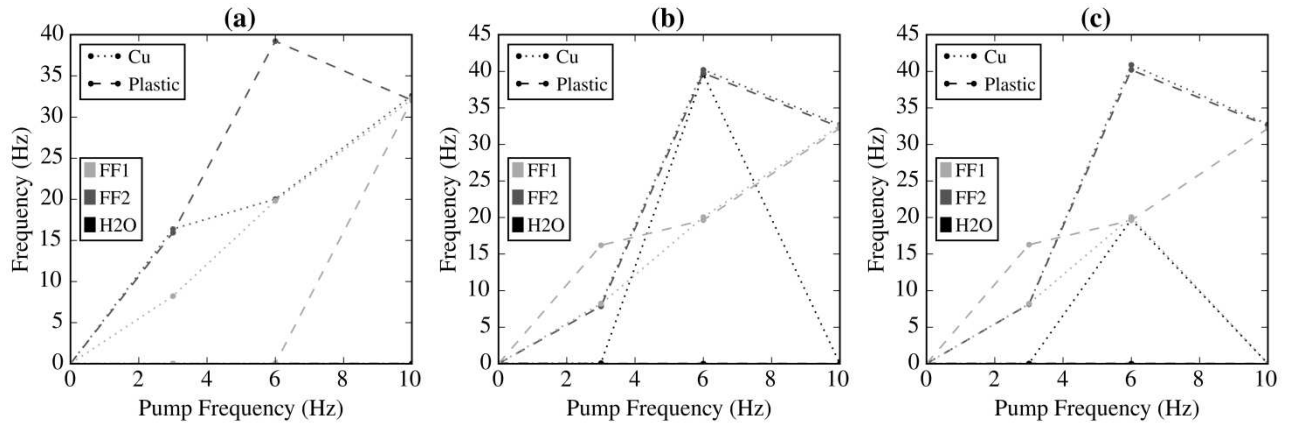


Figure 7. Frequency of maximum amplitude spectrum component vs. pump frequency for tests with two bias magnets. Magnet spacing: (a) 10.2 cm, (b) 15.2 cm, and (c) 20.3 cm.

As shown in Figs. 5-7 the prominent oscillation frequency of the induced voltage may vary erratically when the working fluid is water, or when the working fluid is a ferrofluid when no bias magnets are present or the pumping speed is zero. This is due to little or no voltage being induced in the solenoid under these circumstances, so the measured voltage is essentially noise. Assuming the prominent voltage oscillation frequency is solely a function of the system's

hydrodynamics, each ferrofluid/solenoid core combination should yield a prominent voltage oscillation frequency vs. pumping speed relationship that is independent of the number and spacing of bias magnets (at nonzero pumping speeds). This prominent voltage frequency should increase along with pump frequency for configurations with ferrofluid and bias magnets. As this is not the case, more investigation is needed to better model the system. This will give more insight into the frequency behavior of the induced signal.

4. CONCLUSIONS

The experiment detailed in this report confirms that a measureable voltage can be produced in a solenoid via circulated ferrofluid and that a stronger bias magnetic field results in larger generated voltage. It was also observed that the voltage generation is not significantly affected by the presence of thin copper shielding between the solenoid and the ferrofluid.

In potential applications, ferrofluidic induction may not be optimal for systems where "purchased" energy is expended to propel the fluid. A diverging magnetic field increases the viscosity of a ferrofluid, and would thus increase fluid losses in the system. Also, since electromagnetic induction removes energy from the fluid flow, (by energy conservation) ferrofluidic induction would ultimately decrease the efficiency of a powered system. However, ferrofluidic induction could be used to provide a means electrical power generation for passively-driven systems (such as a thermosiphon) with no energy costs and lower efficiency concerns.

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