Novel Methods of Avalanche Duration Measurement

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The emf induced from magnetic fluxes due to the motion of individual beads was measured using a 200-turn copper wire coil. A conical pile made of steel beads sat between two 500-turn Helmholtz coils in a nearly-uniform magnetic field. A pickup coil sat in the plane of the base of the pile. As beads avalanched off of the pile they created a magnetic flux, which in turn induced an emf according to Faraday's Law. We conducted a proof-of-concept experiment to study the feasibility of using induced electromotive force as a means to measure avalanche duration in critical granular systems. The responsiveness, noise, and resolution of the pickup coil were analyzed to determine if the induced emf was large enough to give information about the change in voltage resulting from avalanches, as well as the time duration of avalanches. The small avalanche event and system-spanning event regions were analyzed separately due to limitations in the equipment used. We found reponses at a high resolution for the small avalance event region, but a lower resolution for the system-spanning region. The background noise present in the pickup coil may be drifting over time, which would cause problems in data analysis of the induced emf. Possibilities for data analysis of avalanche duration are presented. Improvements to the apparatus can help reduce some of the noise present in the pickup coil as well as reduce the number of experimental variables that need to be taken into account.

INTRODUCTION

The beadpile experiment has been a topic of research at the College of Wooster for over twenty-five years. It consists of a slowly driven, conical pile of beads that avalanches once it reaches a critical point. The size of each avalanche and the time it occured is measured and sorted into probability distributions based on the size of the avalanche and time between avalanches. Avalanche probability distributions follow trends that scale across different parameters.The idea for the bead pile experiment arose from the sandpile model initially proposed by Per Bak in his seminal work *How Nature Works*, in which he introduces the idea of self-organized criticality. Bak argues that certain natural systems self-organize to a critical point. While the bead pile experiment does not fall under the class of self-organized criticality, it is a critical system whose phenomena closely match theoretical models for the sand pile model, as well as other systems [1]. Criticality is dependent on parameters within a system that build toward critical values and then experience a release of energy which takes the system to sub-critical values [2]. In the case of the beadpile, when beads build to the critical angle of repose then beads are shed from the pile and avalanche off. Critical systems have parameters that can be tuned and cause new behaviors to arise. In the case of the beadpile, a number of different parameters have been studied at the College of Wooster over the past twenty-five years. In this experiment, we are testing a novel method of measuring a new parameter, the time duration of avalanches.

History

Conical granular pile experiments began at the College of Wooster in 1989 when students adapted Bak's sandpile model to a conical pile of beads [3]. Researchers examined several parameters, including density, coefficient of friction, coefficient of restitution, pile size, drop height, and drop area. Specifically, they studied those parameters' effect on avalanche size and time distribution statistics. The bead pile was found to be scale-invariant for pile size, drop height, and drop area, while the coefficient of friction, coeffiecient of resitution, and density of the beads had no effect on pile statistics [4]. However, other parameters have not yet been studied for the bead pile which have effects on avalanche dynamics.

The current form of the bead pile experiment began in 2008 when student researchers noticed deviations from previous data in avalanche size probability distributions. The cause was found to be a stickiness on the beads, which caused a systematic deviation from expected behavior, similar to other tuning parameters. Researchers began examining the effects of cohesion *and* drop height on avalanche statistics. Helmholtz coils were used to create a uniform magnetic field, which created cohesion between steel beads and could easily be tuned. Results showed that the size of avalanches changed predictably with cohesion [5]. Increasing cohesion caused an increase in the probability of small and large avalanches, with a decrease in mid-sized avalanches. Small avalanche events and large avalanche events, also called system-spanning avalanches, appeared to exhibit two different types of probability distribution. Since then, researchers at the College of Wooster have been working on understanding the interplay of cohesion and drop height.

Specifically, we have been studying the effects of cohesion on avalanche size and inter-event time statistics. Using two Helmholtz coils, a uniform magnetic field can be generated which causes magnetically-susceptible beads to resist avalanching. Previous researchers have shown that varying levels of cohesion can have impacts on the probability distributions of both size and inter-event time [5]. However, in order to develop a better understanding of the effects of cohesion more parameters need to be studied.

The time duration of avalanches can give us further insight into how well the bead pile adheres to current theories of criticality for granular material. Theorists have developed models to predict how long avalanches should last at different levels of cohesion. Susan Lehman at the College of Wooster and Karin Dahmen at the University of Illinois Urbana-Champaign proposed altering the bead pile apparatus in order to measure the duration of avalanches [6]. One proposed technique was to use the flux generated by avalanching metal beads in the magnetic field to induce a current in a third coil. The induced emf over time could be recorded and the duration of avalanches could be calculated from the length of the emf's signal. Experimental studies of avalanche duration have occurred before, but not for the 3-dimensional conical pile geometry. G. R. Maktadbaran and F. Ebrahimi studied the time duration of avalanches in a weakly perturbed conical sandpile contained by a rectangular silo [7]. Maktadbaran and Ebrahimi perturbed the pile discretely, then measured the size of avalanches off of the pile and the relaxation period, or time duration, of avalanches. They found a power-law relationship in the probability distribution function for avalanche duration. Their results matched current theory for 1-dimensional sandpiles. However, while they provide promising statistics for 1-dimensional models, we are interested in expanding time duration analysis to our 3-dimensional system.

New Methods and Primary Motivation

Using magnetic fields and induced emfs to measure physical phenomena is a technique that has been applied to other systems before. D. Eckert, *et al.* moved strong magnets through coils of copper wire, also called pickup coils, to detect the magnetization of ferromagnetic samples [8]. However, they used permanently magnetized metals to induce a flux, as opposed to an exterior magnetic field. We intend to pursue a similar test, but with a stationary magnetic field and random avalanching causing the induced emf, as opposed to human-caused induction.

In the bead pile experiment tuned for cohesion, we are concerned with examining the interplay of two different types of avalanches: small avalanche events and system-spanning avalanches. The small avalanche events are those observed without the effects of cohesion and typically fall below a certain size threshold depending on the dimensions of the pile. System-spanning avalanches are considered to be large-scale events which occur over the entirety of the pile surface. Because system-spanning avalanches generate substantially more flux in the pickup coil than small avalanche events, these two types of events cannot both currently be detected within a given test run. Thus, separate tests were developed for each type of avalanche.

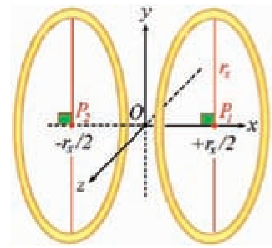

FIG. 1: The magnetic field generated by a pair of Helmholtz coils a distance x away from the center points P_1 and P_2. Image credit to P. Beiranvand [10].

For this experiment we will use a similar experimental apparatus to previous bead piles that are tuned for cohesion. A third coil will be placed in the magnetic field of the Helmholtz coils to measure any magnetic flux by recording an induced current. We can then study the duration of avalanches by examining the duration of the voltage signal produced. This is a proof-of-concept experiment, so we are mainly focused on determining whether or not we can generate measurable signals from the flux caused by beads moving in the field. If we can demonstrate measurable signals, then we can begin to analyze the resolution of the signals generated at various sensitivities, as well as begin testing methods for data analysis.

THEORY

A nearly-uniform magnetic field $\mathbf{B}$ exists between the two Helmholtz coils. As current is increased through the wire of the Helmholtz coils, the strength of the field increases. The strength of the magnetic field between Helmholtz coils may be calculated by the Biot-Savart law and found to be

$$B = \frac{\mu_0 N I r^2}{(r^2 + \frac{x^2}{4})^{\frac{3}{2}}} \tag{1}$$

where μ_0 is the permeability of free space, N is the number of turns of the coil, I is the current passed through the coils, r is the radius of each coil, and x is the distance between the coils [9]. Fig. 1 shows the relationship of the variables in Eqn. 1 to a physical system. In order to create a uniform field, the coils must be separated a distance r apart from the inside rim.

A pickup coil is situated a distance $d_b = 3.1$ cm from the bottom coil and a distance $d_t = 4.6$ cm from the top coil. Each coil is 2.1 cm in thickness. The distance is measured from the nearest side of the Helmholtz coils to the nearest side of the pickup coil. Faraday's Law tells us that a changing magnetic field induces an electric field [9]. When in the prescence of conducting materials, this induced electric field becomes a current. Mathematically, Faraday's Law is given by

$$\mathcal{E} = \oint \mathbf{E} \cdot d\mathbf{l} \tag{2}$$

where $\mathcal{E}$ is the motional emf induced in the pickup coil, $\mathbf{E}$ is the strength of the electric field induced, and $d\mathbf{l}$ is a differential element of the copper wire conducting the current. The change in $\mathbf{E}$ is related to the change in the magnetic field by

$$\oint \mathbf{E} \cdot d\mathbf{l} = -\oint \frac{\partial \mathbf{B}}{\partial t} \cdot d\mathbf{a} \tag{3}$$

where $d\mathbf{a}$ is a differential element of the area that $\mathbf{B}$ covers. Notice that the right hand side of Eqn. 3 is the surface integral of a vector field. This type of integral, mathematically, defines the integral of a time derivative of a flux. Since $\mathbf{B}$ is uniform and the area $\mathbf{A}$ is constant, we can define the flux as $\Phi = \mathbf{B} \cdot \mathbf{A}$. The emf induced in the pickup coil is equal to the time derivative of the flux, which can be stated as

$$\mathcal{E} = -\dot{\Phi} = \frac{-\partial \mathbf{B}}{\partial t} \cdot \mathbf{A} \tag{4}$$

which is the mathematical statement of Faraday's law that pertains to this experiment.

EXPERIMENTAL APPARATUS

We have adapted a base from previous versions of the bead pile apparatus, which used a circular wooden disk with beads glued on top. The diameter of the base is 18 cm, consisting of steel shot beads of diameter 3.0 ± 0.01 mm. A conical pile of steel shot beads, of the same diameter, sit on top of the base. The bead pile sits between two PASCO EM-6711 Helmholtz coils, each with a diameter of $2r = 21$ cm and 500 turns of copper wire. The coils sit a distance $r = 10.5$ cm apart from rim to rim. The Helmholtz coils are used to create a nearly uniform magnetic field across the pile. The coils are wired in series to an Agilent E3617A power supply, with a maximum DC output of 1 A.

The apparatus used in this experiment involves a few slight modifications to previous versions. A basic view of the apparatus can be seen in Fig. 2. First of all, a PASCO EM-6711 induction (pickup) coil sits at the base of the pile, a distance $r_b = 3.1$ cm from the bottom coil and $r_t = 4.6$ cm from the top coil. All coils have a thickness of 2.3 cm. A Stanford Experiments SR570 current preamplifier is wired in series with the pickup coil. The current preamplifier is used to amplify the current induced in the pickup coils and eliminate some noise that is generated. Various settings of the preamplifier were tested to find the best possible signal that could be produced. The entire apparatus sits upon an optical bench and is supported by aluminum rods and clamps. The complete apparatus setup can be seen in Fig. 3. All of the parts used to support the experiment, with the exception of the optical bench, are made of aluminum. Any

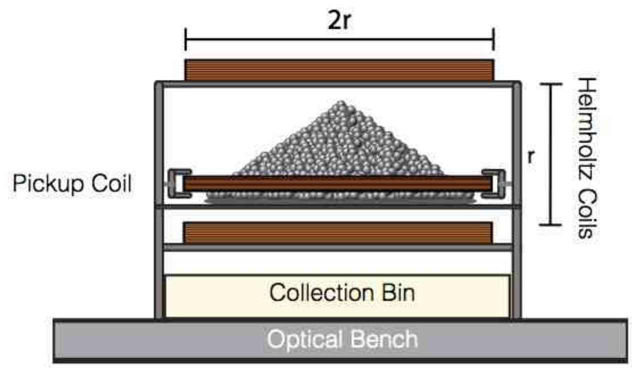

FIG. 2: The basic setup of the experimental apparatus. All parts are supported by aluminum rods secured onto an optical bench. The pickup coil sits at a height approximately the same as the base of the pile.

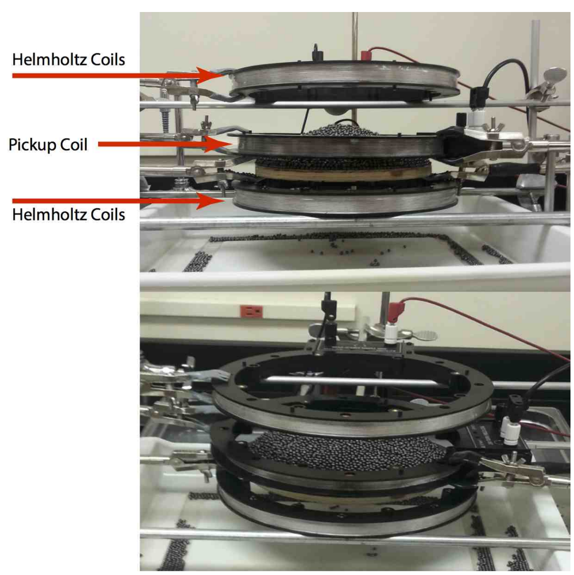

FIG. 3: The beadpile with pickup coil added. The top picture is a side-on view while the bottom picture shows the full shape of the coils being used as well as the optical bench. All supports used were aluminum.

type of magnetically-susceptible metal would influence the uniformity of the magnetic field generated. A plastic bin sits below the bead pile to collect any avalanches.

Tests conducted for small avalanche events used the low-pass filter setting on the current preamplifier. The high bandwidth (low-Q bandpass) filter setting was used for system-spanning avalanches because it allowed a greater range of induced emfs to be detected. Allowing a large range of currents, combined with lowered sensitivity, reduced the chance that the preamplifier would overload during large-sized avalanches or avalanches of a long duration.

A National Instruments USB-6009 Data Acquisition (DAQ) box was used to measure the voltage from the current preamplifier. Digital GPIO pins connected to a USB imported the information onto a Mac. The LabView program NIDataLogger recorded the voltage over time.

Limitations

I. Overload Issues

The SR-570 current preamplifier has a maximum load capacity of ± 5 V. The sensitivity setting of the preamplifier determines how easily this maximum load can be reached. For example, when the pre-amplifier is set to a low-pass filter and a sensitivity of 1 pA/V, an overload can be reached by an avalanche of only a few dozen beads. A small range of measureable avalanche sizes presents a problem when recording data: we want to be able to detect *all* avalanche events, but the range of possible avalanches varies widely depending on the cohesion, type of bead used, and how close the pile is to super-critical. The beadpile experiment's avalanches are inherently probabilistic and random, thus we cannot predict whether small or system-spanning events will occur when a bead is dropped. High sensitivity settings can easily cause an overload, which damages the equipment we are using. Furthermore, extremely large avalanches would not be fully registered if they exceeded the maximum load capacity, ± 5 V.

We switched between the low-pass filter setting and high-bandwidth setting to study the two avalanche regimes separately. The low-pass filter had significantly less noise in the signal, while the high-bandwidth setting had a greater range of detection, without overload. The drawback is that the high-bandwidth setting has more noise and less resolution, which means that not all avalanches could be measured at the same sensitivity. Data runs were taken at a number of different settings depending on the phenomenon we were trying to observe.

II. Sensitivity

The particular PASCO EM-6711 coil that we used was a *very* sensitive piece of equipment. At the highest sensitivity settings, which were used to detect small avalanche events, even the smallest flux was detected. It was found that moving a metal chair from underneath the apparatus could induce a flux large enough to overload the current-preamplifier. Furthermore, if any type of magnetically-susceptible metal was moved at any velocity near the apparatus, including some wristwatches, the flux was detected and an emf was induced. The full detection range of the pickup coil was about a two meter radius at the highest current value. If a strong magnet was moved quickly through space at this distance, an emf was induced that was just larger than the noise level.

III. Environment

The apparatus was constructed in a basement laboratory near other electronics. The signals from these electronics may have contributed to some of the noise present within the coil. First of all, the pickup coil sat near a standard United States wall outlet, which has a frequency of 60 Hz. The power supply, oscilloscope, and current preamplifier may also have contributed to any background noise present within the pickup coil. Furthermore, vibrations from the table could cause slight movements in the Helmholtz coils, which changed the magnetic field and induced the flux. Modifications were made to the apparatus so that the three coils were stuck rigidly in place.

Due to this extreme sensitivity, the results being recorded were diligently monitored as data were taken. Despite these issues, the pickup coil had low noise and the signal resolution was not greatly affected at high sensitivity settings. During experimentation, care was taken to not touch the table, apparatus, or in any way cause vibrations which may have induced an emf. Furthermore, all magnetically-susceptible metals possible were removed from around the apparatus to prevent accidental fluxes.

PROCEDURE

Since this is a new apparatus we are primarily concerned with the feasibility of measuring phenomena with this method. If we can show that the concept works, then we would like to look into the noise present in the pickup coil and the resolution of the instruments being used. Testing for this experiment can be split into the above stated parts.

Proof of Concept

We first need to look at whether or not it is possible to use this apparatus to measure avalanches. To test the usefulness of the pickup coil, we recorded the voltage signal from the pickup coil using the NI-DAQ as the pile was perturbed. A variety of different settings were tested in order to determine the responsiveness of the signal as various magnitudes of beads moved through the

TABLE I: The different settings on the current preamplifier that were tested to check the responsiveness of the pickup coil to magnetic flux. Settings 4 and 5 were chosen for the small avalanche and large avalanche regimes, respectively.

Setting	**I** Offset	Filter Frequency	Sensitivity	Filter Mode
1	+50 pA	3,000 Hz	100 pA/V	Low Noise
2	+5 nA	3,000 Hz	100 pA/V	Low Noise
3	+5 nA	3,000 Hz	1 pA/V	Low Noise
4	Off	10 Hz	1 pA/V	Low Noise
5	$5\,\mu$A	10 Hz	$5 \times 100\,\mu$A	High Bandwidth

magnetic field. All of these settings were examined with currents of 250, 500, 750, and 1000 mA passing through the Helmholtz coils.

Table I shows the various settings for the current-preamplifier that were used to record data. We determined that Settings 4 and 5 gave the best signal, in terms of noise level and responsiveness to flux. Those two settings were used for all data recorded in this paper. Setting 4 was used to test small avalanche events, while Setting 5 was used to test system-spanning avalanches. In order to determine whether or not a measurable signal could be produced by beads moving through the field, various amounts of beads were dropped onto the pile and the signal was recorded. We defined a measurable signal as a noticeable increases in the voltage, above the range of the noise level. If the change in voltage is large enough to see on any reasonable scale, then the induced emf would be measureable. To identify whether or not a measurable emf could be generated, we dropped various numbers of beads onto the apex of the pile and recorded the signal over time. Avalanches were also caused by hand to observe the effects of beads moving on top of the pile, as opposed to falling through the field and onto the pile. The proof of concept test's purpose was to observe the resulting voltage from bead movement.

Noise

Any background noise in the pickup coil, current preamplifier, or DAQ can possibly mask the detection of avalanches if the induced emf falls within the range of the base noise of the system. Data runs were taken at both Setting 4 and 5 in order to determine the background noise at each setting. The noise voltage in the pickup coil was recorded over time, during which no beads were dropped on the pile. The noise was analyzed for its range, as well as qualitative features such as drifting and constancy.

The base noise is the range of voltages that we expect the pickup coil to have when no beads are moving in the magnetic field. Testing for noise will involve examining the average value and range of the noise. The average value will tell us more about whether or not the background noise is drifting because our voltage should be constant, within a range, throughout the entire run. The range of the background noise will tell us more information about the resolution of the pickup coil and the size of events that we will be able to detect in each regime.

Resolution

Qualitative tests were done on the resolution of the pickup coil. For small avalanche events, we are looking to find the smallest possible event that can induce a measureable current in the pickup coil. For this part of the experiment, Setting 4 from Table I was used. Most importantly, the current pre-amplifier was set to a low-pass noise filter setting. To find the minimum possible resolution, or the smallest event that could be detected, the current preamplifier was set to the a sensitivity of 1 pA/V. Beads were dropped onto the apex of the pile and the voltage signal resulting from the induced emf was recorded.

We defined the maximum resolution as the lowest necessary sensitivity to detect avalanches while also not causing a signal overload in the current preamplifier. The method for determining this sensitivity level was to push multiple beads off of the surface of the pile and determine if the preamplifier would overload. The minimum sensitivity setting, where the preamplifier was not overloaded, was used. We want to determine the setting with the greatest possible range of detection. However, by changing the sensitivity we are also limiting the minimum sized avalanche that could be detected. If the sensitivity was set too low, no flux would be detected. Setting 5 from Table I was used for these experiments.

The maximum sensitivity setting used was $5 \times 100\,\mu$A/V. Data were taken with a current through the coils of $I = 500$ mA. In order to determine the smallest possible event that could be detected at this setting, a different number of beads was dropped onto the apex of the pile. Either 1, 5, 10, 20, 50, or 100 beads were dropped onto the pile at once and the voltage signal produced from the induced emf was recorded.

RESULTS AND ANALYSIS

Proof of Concept

Once the apparatus was built, we began perturbing the pile to see what kind of signal was generated. Negative spikes in voltage correspond to the bead falling through the field toward the pile, while the following positive spike in voltage is the result of Lenz's Law as the coil tries to maintain the flux that was momentarily present. Figure 4 shows an example of the signal response for small

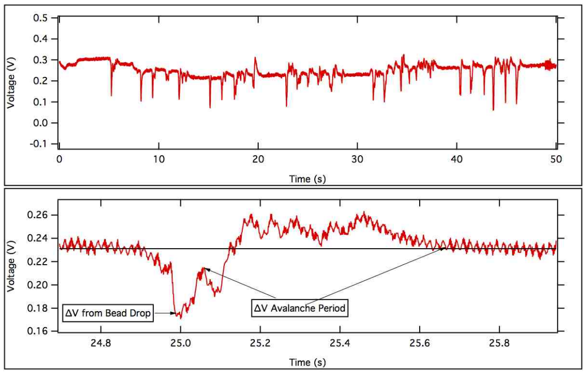

FIG. 4: a) The voltage over time as single beads are dropped onto the pile. The downward spikes in voltage indicate detection of the bead drop. b) A close-up of the resulting avalanche from a single bead drop. The black line represents the base noise of the signal before and after the event.

avalanche events when a single bead was dropped on the apex of the pile.

In Figure 4.b, the voltage change due to an avalanching is shown. Notice that avalanches do not cause sharp peaks in the same way that a bead drop does, but rather a sustained signal followed by a graudally decreasing voltage back to the base noise level. There does appear to be some drifting in the signal. The signal in Figure 4.a begins with a base noise around 0.3 V, but decreases to around 0.2 V after the first bead drop. This drift could cause issues with data analysis. If the background noise is consistently drifting then analysis of the change in voltage may be skewed positively or negatively. If an avalanche occurs while the signal is drifting we may identify a larger or smaller change in voltage than what actually occurred.

Noise

Noise runs for the small avalanche event settings in the pickup coil at various current values are shown in Fig. 5. The average and range of all noise runs are displayed in Table II. The ranges of the noise signal for small avalanche event settings all fell below 0.1 V, which is well below the induced emf for an avalanche of a few beads.

TABLE II: Average voltage values for noise runs taken with different amounts of current through the Helmholtz coils.

Avalanche Type	Current (mA)	Average (V)	Range (V)
Small Events	1000	0.19	0.08
	750	0.25	0.03
	500	0.27	0.04
	250	0.23	0.05
System Spanning	1000	-0.46	1.06
	750	-0.45	1.09
	500	-0.35	0.54
	250	-0.36	0.39

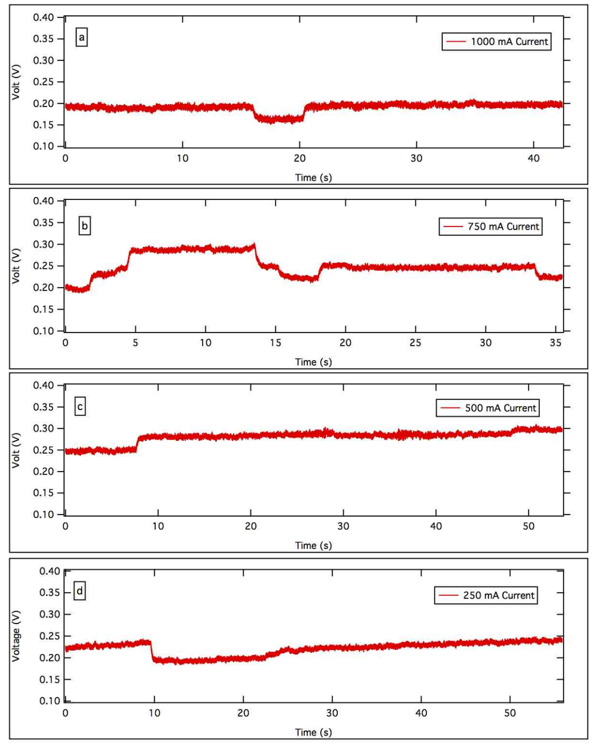

FIG. 5: Noise in the pickup coil for small avalanche event settings at a) 1000 mA, b) 750 mA, c) 500 mA, and d) 250 mA current through the Helmholtz coils.

For the small avalanche event settings there is drifting occuring in all of the data runs taken. Figure 5.b drifts positively by 0.1 V over a 5-second period. The other noise runs for these settings do not exhibit the same type of drifting, but do display sudden jumps in base voltage. Drifting and quick changes in base voltage can have an effect on the data recorded, as they will skew changes in voltage due to avalanches. These data runs were taken over inconsistent, short periods of time. While these phenomena may be displayed by the reported data runs, more noise testing needs to be done to observe if drifting or jumps will have an effect on the signal for long data runs.

For the system-spanning event settings, drifting is not observable. This may be because the wide range of the base voltage masks drifting and averages out any sudden jumps. The average and range of the noise for Setting 5 can also be found in Table II.

The noise tests for system-spanning avalanches are shown in Fig. 6. The ranges of noise for system-spanning avalanche settings vary more drastically, ranging from 0.39 V at 250 mA through the Helmholtz coils to 1.09 V at 750 mA through the Helmholtz coils. The wide range of average voltages when the pile is not perturbed means that the resolution of the pickup coil could vary significantly depending on the current through the Helmholtz coils.

Resolution

The smallest possible event that can be detected on the small-avalanche event settings is a single bead moving through the magnetic field, as evidenced previously by Fig. 4. For the system-spanning avalanche settings we expect a much lower resolution. Figure 7 shows the signal produced by various number of beads being dropped on the apex of the pile at once.

Fig. 7.a-c all show noticeable changes in voltage due to the induced emf. The spike from the initial bead drop is well beyond the threshold of the base noise. However, for the resulting avalanches, the change in voltage is not much higher than the range of the noise. Analysis of avalanche duration for large-scale avalanches will be difficult unless the the noise is decreased at this sensitivity or the avalanches are much bigger than 100 beads. Several fluctuations in voltage occur when many beads are dropped on the pile, making it difficult to separate the ΔV due to the beads from the ΔV due to avalanching. For bead drops that were 10 beads or less the induced emf from the initial drop was barely larger than the base noise range. While the initial bead drop is noticeable for Fig 7 .d-f, the resulting avalanche falls below the range of the base noise.

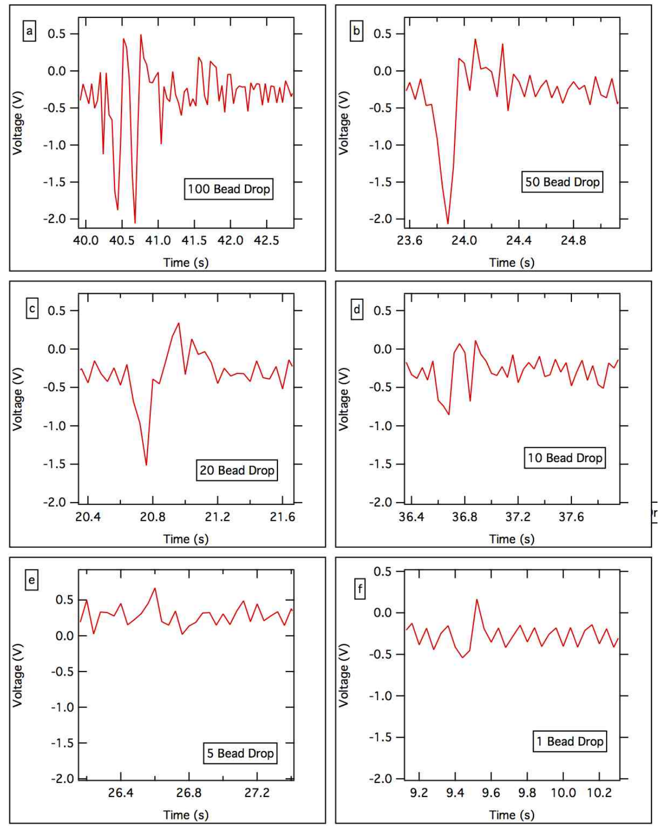

FIG. 7: Signals produced by various amounts of bead drops onto the apex of the pile over time. Clusters of beads were dropped onto the pile at one time in groups of a) 100 beads, b) 50 beads, c) 20 beads, d) 10 beads, e) 5 beads, and f) 1 bead. Both the initial voltage change and the voltage change due to avalanching were examined.

It should be noted that the resolution test we carried out is more of an analysis of the induced emf due to the initial falling beads, not necessarily the resulting avalanches. We can control how many beads we drop, but we cannot control how many beads fall off of the pile as a result. The movement and number of beads that resulted from bead drops during this resolution test was not of the same magnitude every time, so there is variability in the signal produced. However, it is apparent that at least fifty beads need to be moving in the magnetic field at these settings for us to be able to detect any useful change in voltage, based on the results from resolution tests. The induced emf caused by 10 or fewer beads was not enough to analyze.

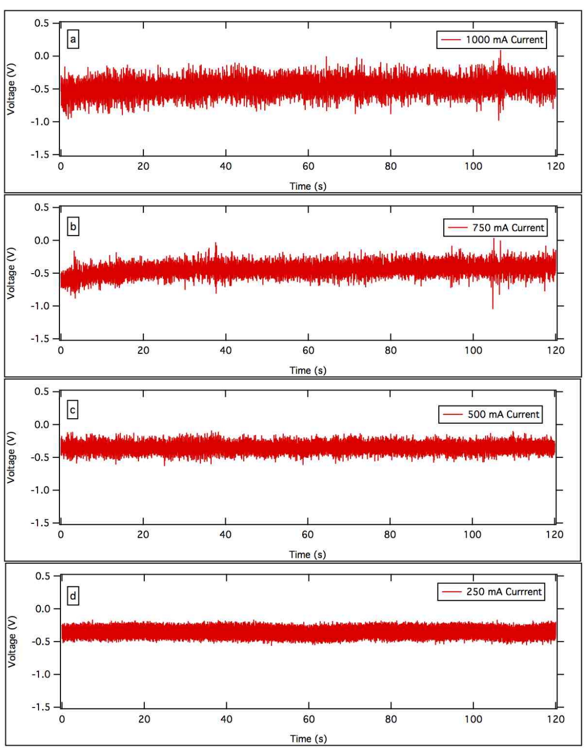

FIG. 6: Noise in the pickup coil for small avalanche event settings. Data was taken at a) 1000 mA, b) 750 mA, c) 500 mA, and d) 250 mA.

FUTURE WORK

Apparatus Improvements

The experimental apparatus needs to be improved before rigorous testing can be done using the pickup coil. First of all, the three coils need stabilizing rods between one another in order to ensure rigidity and prevent vibration. If any single one of the coils moves in any way then a large emf will be induced. It does not matter which coil moves, only the relative motion of the coils to one another.

Secondly, some form of shielding needs to be added to contain the detection range of the pickup coil to only within the Helmholtz coils. As of right now, the two meter radius of detection for magnetic flux is too much of an experimental variable to ignore. Adding shielding may also decrease some noise within the pickup coil, because the coil will be shielded from the natural frequencies of surrounding electronics.

Finally, a preamplifier with a larger dynamic range needs to be added to the apparatus to replace the current preamplifier used for these tests. If the pickup coil is going to be used for full data runs of the bead pile experiment then it needs to be able to handle avalanches of all sizes, especially when cohesion is turned up. Our understanding of the pickup coil's behavior will also improve if we can match up changes in voltage from the signal to changes in mass from the data currently being recorded.

Possible Data Analysis Techniques

In terms of long-term applications for this apparatus, we are concerned with how well we can measure both the change in voltage ΔV and the duration of the avalanches Δt. If we are going to measure the duration of avalanches, we need to be able to identify when the avalanches occur in the voltage vs. time graphs. The recorded data from the resolution tests were analyzed for 5, 10, 20, 50, and 100 bead drops.

Fig. 8 shows an example of the voltage change in the small events regime. The total change in voltage per drop can be calculated as $\Delta V = \Delta V_2 - \Delta V_1$. The duration of the avalanche can also be measured, using $\Delta t = \Delta t_2 - \Delta t_1$. For system-spanning avalanches, the ΔV and Δt values were more difficult to define because the voltage often fluctuated many times between positive and negative change, both during the bead drop and during the avalanche period. To determine ΔV and Δt for system-spanning avalanches more work needs to be done on how to create a clear signal for these events. One possible solution is to use wave smoothing to better define the change in voltage from the change due to noise. The method used for system-spanning tests is not sound enough to accurately measure the duration of avalanches.

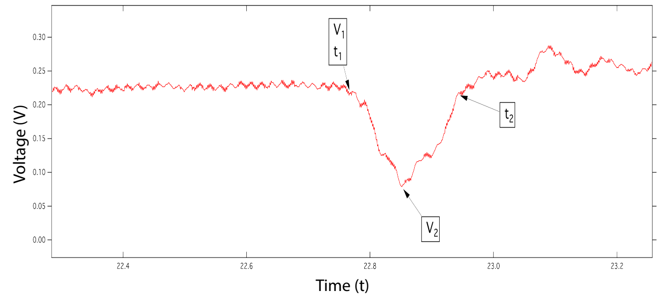

FIG. 8: A graph of the change in voltage resulting from a single bead being dropped on the pile. Points V_n and t_n were used to calculate the change in voltage and duration of the induced emf.

CONCLUSION

A conical pile of steel beads placed in a uniform magnetic field can cause magnetic fluxes when beads avalanche off the edge of the pile. We have found that the magnetic flux due to moving steel beads is large enough to induce a measureable current in a 200-turn, copper wire pickup coil. The pickup coil is sensitive enough to measure a single bead moving through the magnetic field, but can also handle the induced emf due to hundreds of beads avalanching.

The equipment used in the experiment presented some limitations to our ability to measure the signal resulting from the voltage of the pickup coil. Small events and system-spanning events had to be studied separately because our current-preamplifier could not handle large fluxes at high sensitivity, and could not detect small fluxes at low sensititivity. The noise present in the pickup coil, in its current environment, has a small enough range to make the implementation of this apparatus worthwhile. However, further noise analysis needs to be completed to investigate the possibility of the voltage drifting over time.

Improvements to the apparatus, such as rigidly attaching the Helmholtz and pickup coils to each other, would significanlty reduce the number of variables that could have an effect on the signal. Furthermore, shielding the pickup coil so that it can only detect flux within the Helmholtz coils would also decrease the number of variables. The next step for the pickup coil is implementation into a slowly-driven, discrete beadpile experiment so that data about avalanche size can be compared with the values obtained from the induced emf.

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