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Repair and Characterization of a Wimshurst Machine

Introduction

From the outset, when searching for a topic to explore with my senior seminar, I knew I wanted it to be something experimental, applied, hands-on. While I understand and appreciate the value of the abstract and theoretical side of physics, my interest has always been with what we can do, not so much why. The 'why' is important because understanding it allows for the discovery of new applications of the knowledge, but I can only be truly motivated to explore the abstract in relation to a physical project that has spurred my interest, not simply for its own sake. What I really love is the nuts and bolts of science, the machines and tools scientists use, seeing the theories and laws I learned in class actually happening in the real world, right in front of my eyes. Given this attitude, when I first glimpsed the Wimshurst machine I was, unsurprisingly, immediately enthralled. The ancient machine was perfect for my purposes, mechanical and intriguing and dramatically presenting basic electrical properties I had been taught. Repairing its components allowed me to utilize my existing knowledge and gave me the impetus to learn more, while discovering the early process of its development helped me put my understanding in a historical context. I have thoroughly enjoyed the project and feel that I have greatly benefited from the endeavor.

Background

To understand the Wimshurst machine, it helps to have some background as to the level of technological and scientific progress at the time when was first developed. Electrical properties had actually been known about for literally millennia before the Wimshurst machine was ever conceived. Ancient Greeks such as Thales, around 600 BC, studied the way that a chunk of amber rubbed with fur would attract pieces of magnetite. Such an effect was due to static electricity, though he attributed it to magnetism like that associated with lodestone. For centuries, no real use was found for electricity and it wasn't until the 1600s when it was finally found to be separate from magnetism by an Englishman named William Gilbert (Stewart). Gilbert is also responsible for coining the term "electric" from the Greek word for amber (Baigrie). After this point, development of electrical technology picked up speed. In the 1700s, early capacitors were created called "Leyden Jars," of which more will be said subsequently considering their integral part in the Wimshurst apparatus. The early 1800s saw great leaps forward in electrical knowledge, with contributions from the great names in the field: Volta, Ampére, Faraday, and Ohm (Kirby). Later in the century, electrical engineering took off, dominated by Tesla, Edison, Bell, and Kelvin. In this environment of interest in electricity generation, the Wimshurst machine itself was created, developed by an English inventor, James Wimshurst, around 1880 (Slatt).

History of the Wimshurst Machine

The Wimshurst machine was unique amongst the electrical machines that came both before and after it in that friction wasn't necessary for its operation. Preceding it were friction generators which involved disparate materials, such as glass and lubricated leather, rubbing against each other in order to separate charges (Pender). After it, came the famous Van de Graaf, which again involved friction – this time between its metal spheres and a silk belt. However, Wimshurst's device and others of its ilk, called "influence machines," functioned using electrostatic induction. The name "influence" came from the fact that the moving parts in the machines didn't need to touch but still affected each other by being oriented in close proximity to one another.

Several such machines were developed, including designs by Holtz and Toepler, but that of Wimshurst was the most effective. All others were known to be heavily hindered by the weather, ceasing to function in humid climes, and Holtz's machine had a tendency to reverse polarity if the gap between its terminals was larger than the distance a spark could jump. The Wimshurst machine could function regardless of the humidity and its polarity was constant, giving it clear superiority over its brethren (Pender). In its heyday, it saw various usages in the medical field especially in powering X-ray machines, which were gaining prominence, and in direct application to patients as electroshock therapy (Slatt). The ability of the machine to generate high voltages opened up many avenues into electrical research, but its applications weren't limited to science. A popular Victorian-era parlor game called the "electric kiss" revolved around the Wimshurst machine, wherein a man and woman would each touch one terminal and then let a spark fly as their lips met (Slatt). Currently, Wimshurst machines are still manufactured, primarily for demonstration purposes in science classes.

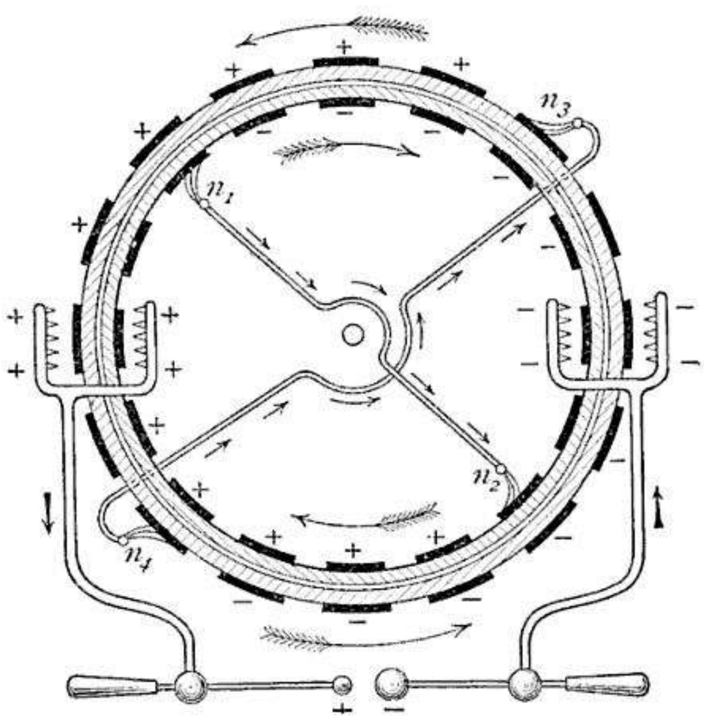
History of Leyden Jars

Of import at least as great as the Wimshurst machine, both historically and to my project, is the Leyden jar. Drawing its name from the University of Leyden in Holland where it was developed by Pieter van Musschenbroek, the early capacitor allowed engineers and scientists in the growing area of electricity to store charge for later use. Musschenbroek's assistant was among the first to experience the power of the Leyden jar, being shocked during a test and failing to recover fully for two days after (Pender). The Leyden jar was of critical importance not only in Europe, but in the Americas as well. The gift of a Leyden jar stirred Benjamin Franklin's interest in electricity and he performed the then most comprehensive characterization of the capacitors and used them in his extensive electrical research. Among his results was the invention of the lightning rod to protect buildings from storm discharges (Miller). However, in this paper what is most important in regards to the Leyden jar, is its combination with the Wimshurst device wherein the influence machine charges the capacitor. A discussion of how this works follows.

How the Wimshurst Machine Works

Central to understanding the Wimshurst machine is a comprehension of electrostatic induction. Take two bodies, A which is negatively charged and B which is neutral. Moving A close to B draws the internal positive charges in B toward A, while at the same time pushing away the negative which results in a separation of charges. If B is then grounded, its negative charges are siphoned off leaving only the positive. Once the ground wire is removed, a force of attraction exists between positive B and negative A. If the two bodies are pulled apart to a distance where they no longer have a significant affect on one another, energy is needed to overcome the attractive force. This energy manifests in the positive charge that now exists independently on B, which has thus been charged through “influence,” i.e. induction (Miller).

The Wimshurst machine relies on induction to work. The metal sectors around its disks have an inherent charge, simply from the way they were made and handled. The charges between sectors opposite each other on the two disks will not be the same, so an imbalance is present and a charge induced. Consider only the outer (rear) disk in the diagram below.



As the positive charge (from the sector’s initial state) is rotated to the left on the disk it induces negative charges on the front disk. It proceeds until it reaches the collecting comb which draws charge off of the disk to be stored in the attached Leyden jar. The remaining positive charge not collected continues around and reaches the neutralizing brush. The brush is attached to a rod making a short circuit across the disk, which the positive charges take since the opposite side is negatively charged due to the other disk and initial induction. Continuing around the edge of the outer disk, only negative charges remain and are collected by the other comb. The negative charges not removed reach the other side of the neutralizer rod and take that path, since the opposite side is positively charged. Then the cycle continues, with the same process happening in reverse on the other disk (Reade and de Queiroz). The Leyden jars allow the charges being collect to also be stored, but when the voltage between the two terminals gets high enough, at the breakdown point for air, a spark leaps across the gap.

My Project

Now that the background and functioning of the Wimshurst machine has been established, on to the particulars of my project. When I began, the machine was in quite a bad state. The belt tension on the pulley system was too low to allow the hand crank to rotate the wheels, one Leyden jar was broken while the foil inside the other was wrinkled and torn, the disks (especially the rear one) were significantly warped, and the neutralizer brushes were rusting and falling apart. Aside from all this, the finish was mostly scraped off giving it a rather rough appearance but getting the machine working, not looking pretty, was my primary concern.

My first action was to replace the broken jar. I had to whittle down the wooden stoppers to get them to fit into the new bottles, because identical glassware was nowhere to be found, even on the internet. This part took quite a bit of scraping with a pocket knife, but I got the stoppers to fit in the new jars. Leyden jars are basically parallel plate capacitors, the glass jar itself forming the dielectric. As the machine had been constructed, the inner conductor/plate was aluminum foil pushed up against the sides and taped or glued. However, research revealed that I had another option. Salt water was actually used as the original inner electrode. After careful consideration, I decided that salt water would be a better option because it didn't involve the hassle of trying to fit wide sheets of foil through the small mouth of the bottle, each wrinkle giving an opportunity for losses to corona discharge. I filled one jar with salt water and popped in the wooden stopper apparatus (metal screw through the stopper, chain descending into the jar to contact the plate/water). It had some effect because as I spun the disks a few times by hand (pulley system wasn't working) I accidentally brushed against a metal component and received a satisfying shock. However, problems immediately arose. I had put the other wooden stopper in the other jar, before putting salt in the water, just to leave the machine in a symmetric appearance while I went to class. Unfortunately, when I came back the stopper had begun to disintegrate, clogging the water with debris. Worse, it had absorbed water and expanded, now being impossible to remove without breaking the jar. After attempts to dry the stopper and wiggle it out I eventually had to break the jar and order a new one. Later, the other jar, which also had become filled with a cloudy rust colored mixture of water and rotted wood, met the same fate. I decided to replace the wooden stoppers with rubber ones that had holes through them to accommodate the metal screws that connect to the water and collectors.

Before replacing everything, I did try to measure the capacitance since I had felt a charge, though no spark would jump the gap at this point. In doing so I learned a valuable lesson, which reinforced my value of applying physics to real projects. I touched the leads of the Dan Brewer's DMM to the sides of the capacitor, thinking nothing of it. The maximum capacitance I'd heard of for a jar close to this small was 1nF, which was actually the value of an early unit of measure of capacitance called the "jar" for this very reason. Such a small capacitance didn't seem to be to any problem, but when I touched the leads to the machine there was a pop and the DMM was dead beyond all help. I knew that C=Q/V but I realized then that memorizing all the formulas in the world doesn't do any good if you don't tie them to what they physically mean. Sure the capacitance was low, but voltage was *inversely* proportional to it – a very high voltage slammed through the meter and burned it out. Also, as Dan reminded me, the capacitor didn't need to be charged to measure it's capacitance, since the value was a ratio, so it was better to do it with the system fully discharged. Lesson learned.

The fact that I did manage to get charge for a while was something of a fluke since the warping of the disks and the corroding brushes made the process seldom function properly. Without the brushes being in constant contact, the short circuit at the neutralizer brushes couldn't occur and the whole process breaks down. The machine soon stopped working again, because of this fact, and so I replaced the brushes since there wasn't much I could do about the disks – that would be more akin to making a new machine than repairing the existing one. First I replaced the brushes with aluminum foil strips, which worked for a little bit but then would bend when the disk warped out and not return to the former state so the foil wouldn't make contact thereafter. I did however make progress with adjusting the orientation of the neutralizer rods. Here I learned a lesson in the value of theoretic knowledge. Initially, I thought that I could probably repair all the obviously broken components of the machine and it would easily work again, but I was wrong. I figured that the brushes just had to touch somewhere, it didn't matter their orientation to one another or to the collectors. Likewise, I thought the collectors just had to go around the disks at some point, not necessarily the sides. However, as is evidenced by the above description and diagram, the design of the machine is very deliberate. The strong same charges on the two disks are only at the left and right sides, while the brushes have to contact higher where the charges are weak and opposite. Also, the neutralizer rods have to make contact with two metal sectors at the same time or no current can flow – I didn't realize they're supposed to make a short circuit. Once I acquired this knowledge, I immediately put the components in the right order and got some charge once again, though still not well enough to make a spark jump the gap.

At about this point the whole spinning-the-disks-by-hand routine was getting old, so I tried taping the string in the pulley system to keep it together. I found that the tape wrapped around the cord actually caught better in the pulley and gave it something to grab onto, so I wrapped tape periodically around the whole string to increase tension, and also create more friction between the pulley and the string so it wouldn't slip. This actually worked for a bit but the string was too frayed to be held together with tape under the stress of rapid rotation and it soon broke. I replaced it with O-ring stock, since it could be spliced together on the machine, the construction of the device preventing an already closed loop from being wrapped into it.

This adjustment worked well, but O-ring stock ended up not being the idea material – it stretched too much and would quickly become bent out of shape after a few rotations, still being tight enough to spin one wheel but not both. I was nearly out of time at this point, and wasn't able to find a new material to fix the pulley system with. The O-ring stock is enough that I can crank the handle and spin one wheel while spinning the other manually which is easier than trying to do both in opposite directions by hand.

Even with the improved, though not perfect, pulley cord, I couldn't get a good spark. Very late in the semester I made the necessary breakthrough. I found some old coaxial cable, like for a television, in the electronics lab and noticed that where it was fraying at the end there was a woven network of multiple semi-stiff copper wires which looked almost exactly like the original brushes but in good condition. I cut the cable into four sections and stripped them, putting them onto the machine in place of the foil brushes. The result was almost immediate. A few cranks later, a spark jumped the gap with a loud crack! It was extremely exciting and rewarding. Just watching the sparks was dramatic enough, but to have been responsible for their creation after much effort was even more satisfying.

Once the machine was fully operational, I began characterizing it. The voltage I found was over 2000 Volts, since the DMM would oscillate between the high 1980s-90s and simply saying that the value was out of range. I wasn't able to locate a way of measuring even higher voltages, so how much above 2000 it is, I can't say. The current measured was about 10A, though it was hard to get a steady reading – with both current and capacitance I just had to watch the meter's values jumping all over for a while and see what numbers they kept coming back to. For capacitance, I found 80pF for the right side jar and 170pF for the left side, presumably due to its larger volume. These values were lower than I expected, since I'd heard about the typical jar being 1nF, that is, 1000pF. However, as it turned out, that value was for a pint jar, while mine were about half that. Furthermore, my jars were only about 2/3 full. Taking these facts, plus the warped disks which likely cause some losses, I think the capacitance value sounds alright. It's possible that going through the machine and systematically trying to eliminate any sharp edges to prevent corona discharges could improve the capacitance, but at this point the semester was almost over and my primary objective of getting the non-functional machine working had been realized.

Conclusion and Future Research

If it wasn't already apparent from the paper, I thoroughly enjoyed this project and learned some valuable lessons as to the merits of both theoretical and applied physics and how both need to work together to get results. The machine itself was very exciting and one day I'd really like to build my own. I've seen some beautiful designs on the internet with clear acrylic disks and shining copper sectors. As far as future research with this particular project, obviously I'm graduating so it's unlikely to go anywhere. However, if I could continue I would definitely replace the O-ring stock belt with a cord that has less stretch to it to really get the pulley system working. After that, I'd try to get all the components to fit and stay together without all the electrical tape that is currently on the machine. I don't think the tape looks bad but it isn't very true to the original design. Other than those aspects, the functionality seem good, so I would focus on making the wooden elements look better, sanding and refinishing them for a smooth, deep luster. All in all, I really like the Wimshurst machine and am thankful for the opportunity to have been able to work on it.

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