1. Introduction

For our final project, we constructed an ionocraft (or "lifter"), a device that achieves flight with no moving parts via corona discharge from a 25 kV wire. Throughout this project, we utilized and built upon many of the skills we learned throughout the semester in BSC. We constructed a driver circuit for a flyback transformer, capable of producing a tunable voltage on the order of 30 kV for operating the lifter. We designed and constructed the lifter, along with an apparatus for restricting its motion to the Z-axis. We then flew the lifter and performed a variety of measurements, including determining the resonance peak of the flyback transformer by measuring the thrust produced by the lifter at various frequencies. We also measured the induced voltage at the base of the lifter apparatus as a function of lifter height, and tried to understand the theoretical basis of our measurements. Our final lifter setup was safe yet effective, and allowed us to precisely control the lifter’s thrust and measure its height. A simple extension of this work work would be to implement a PID feedback mechanism for controlling the lifter’s height using LabView.
2. Theory of Operation

The lifter is a small balsa wood craft with a small high-voltage line suspended above a grounded aluminum-foil skirt. When the voltage gradient between these electrodes exceeds the dielectric breakdown voltage of air (30 kV/cm), an arc will occur. High voltages under this threshold, however, can cause corona discharge: a large electric field between the conductors will accelerate free electrons, which can begin an electron avalanche if they gain enough energy to ionize neutral air molecules over a mean free path. The lifter aims to produce such fields by holding the small HV line at a very high potential.

The positive ions created in the electron avalanche are then accelerated towards the grounded skirt, but collide with neutral air molecules along the way (the more mobile electrons undergo many fewer collisions). This exchange of momentum produces a neutral wind and results in a net upward force on the lifter. We can estimate the maximum thrust attainable by our lifter, which is an equilateral triangle with 15 cm sides. Work by (1) suggests that the velocity of ions in a corona wind carrying a current $I$ is expressed by:

$$v_c = 180\sqrt{P/m} \cdot m/s \cdot A$$  \hspace{1cm} (1)

Since the thrust is $F = m_{air} \cdot v_c = \rho_{air} \cdot A \cdot v_c^2$, for an air density $\rho_{air} = 1.22 \text{ kg/m}^3$ at STP and a cross-sectional area of flow $A$ (assumed to be 1mm wide around the 45 cm perimeter), we find the maximum expected thrust at $P = VI = 50$ W and $V = 25.2$ kV from our lifter to be:

$$F = \rho_{air} \cdot A \cdot 180^2 \frac{P}{V} = 0.0353 \text{ N}$$ \hspace{1cm} (2)

3. Design and Construction

3.1. Lifter

Our lifter consists of a horizontal equilateral triangle with 15 cm sides, with an 8 cm vertical post centered at each corner. The entire frame is made out of 3/32” balsa wood beams attached with cyanoacrylate glue. A 3 cm aluminum foil skirt is draped over the cross-beams and attached to ground via a 35 gauge copper wire. The high-voltage line consists of a 35 gauge bare copper wire wrapped on the vertical posts 3 cm above the skirt. Our first lifter design included two sets of 20 cm cross-beams and was made from 1/4” × 1/8” balsa, for structural strength. However, it proved too heavy to lift and met its untimely end after we lowered the HV line to 2 cm in an attempt to produce more lift, and the HV arced across the support beams to the grounded skirt.

The lifter’s motion is restricted to the Z-axis using by vertical guylines at each corner. These lines are anchored to a particle board base and tied to a plastic sheet mounted on top of an insulating plastic rod, spaced to line up with the corners of the lifter. Each line passes through a
pair of straws mounted vertically on one of the vertical posts of the lifter. The result is that the lifter is free to move 50cm off the base in the Z direction, but is not able to pitch, roll, yaw, or drift in the X or Y directions. The rod holding the tether roof also passes through the lifter itself, adding yet another degree of security on the lifter's physical motion.

Another rod suspends the HV line from one corner of the lifter, while the ground line comes off a different corner and is attached to the base. This configuration ensures that neither lead with short with the lifter, throughout the entire range of the lifter’s motion.

3.2. Power Supply

To generate the voltages necessary to fly the lifter, we used a flyback transformer and driver circuit. We removed the flyback transformer from a CRT monitor; such flybacks resonate in the 100 kHz range and have built-in rectification and smoothing. We decided to drive the flyback externally, with windings around the exposed ferrite core, so we covered all of its pins (except for the ground of the HV secondary) with corona dope, which insulates 15 kV per 0.01 inch, to
eliminate unwanted arcing.

After experimenting with a power BJT, we decided to use a power MOSFET to drive the flyback to avoid the added complications of gate currents affecting our driver. We constructed the driver shown in Figure 4. The circuit consists of a 555 timer in astable mode, producing a square wave with frequencies from 120 to 1150 kHz, with 55% to 90% duty cycles, respectively. The two potentiometers allow us to adjust the frequency with course and fine tuning. The output of the 555 drives a FJET push-pull which drives the gate of the power MOSFET. This push-pull isolates the 555 output from the MOSFET, allowing us to accurately measure the driver frequency without seeing the distortions caused by the MOSFET switching. R1 and C1 are decoupling. The driver circuit is ran off of a 12 VDC supply, while the primary winding on the flyback is powered by 50 VDC rectified and smoothed mains power passed through a variac to control the DC output.

3.3. Safety Considerations

Due to the high voltages involved, safety considerations were a top priority for our team. We worked in large, low-traffic space, and all HV components of the project located behind a desk cordoned off with caution tape. We reviewed HV safety handbooks and consulted with a campus safety coordinator to determine safe distances from which to operate the lifter. We used a ceramic resistor to discharge the power supply capacitors, and an insulated rod to short the lifter to ground after each flight. Although our system used little current at HV, these precautions ensured a safe working environment for us and other members of the lab.
4. Performance and Analysis

4.1. Thrust Control

Using the MOSFET driver and our lightweight design, our lifter performed quite well. At 50 VDC, our HV setup was able to produce up to 25.2 kV with a driving frequency near 195 kHz and a 75% duty cycle. This voltage easily produced sufficient thrust to lift our 2.106 g lifter. Additionally, we found that by detuning the driver off the resonance of the flyback, we could precisely control the thrust produced by the lifter.

To probe the resonance peak of the flyback, we attached various payloads (mounting tape attached symmetrically to the foil skirt) to the lifter, and used a frequency counter to measure to the two drive frequencies, above and below the resonance peak, at which the lifter was neutrally suspended. At these frequencies, the thrust produced matches the weight of the lifter and payload, so this procedure allows us to measure thrust as a function of drive frequency. Our measurements are shown in Figure 5. Our errorbars in thrust are from the measurement of the lifter’s mass; in
reality they are probably larger due to the effects of static friction between the lifter and guylines. However, a general peak is clearly discernible, with a maximum thrust of 0.033 N at 196 kHz, in very good agreement with our prediction from §2. Our maximum payload was 1.23 g, nearly 60% of the mass of the lifter. We note that the half-power width of the peak is greater than 30 kHz, implying \( Q < \frac{196}{30} = 6.53 \).

Fig. 5.— Lifter thrust as a function of drive frequency

4.2. Height Determination

To measure the height of the lifter, we measured the induced potential on a 15 cm \( \times \) 15 cm piece of aluminum foil placed on the wood base beneath the lifter. To prevent the build-up of charge due to catching the ion wind off the lifter, the foil was covered with a piece of plastic, as shown in Figure 2. The signal from the foil was passed through a 10 kHz low-pass filter to eliminate the drive signal, and measured with a DMM. We measured the height of the HV line on the lifter above the wood base and recorded the induced voltage for several positions. Our measurements are shown in Figure 6. The data fit exceptionally well to the power law: \( P(h) = 3.08 \times h^{-1.34} \), where \( h \) is the height of the HV line in meters. This mechanism of height detection works sufficiently well
over the lifter’s range of motion that it could be used in a PID feedback mechanism to control the lifter’s height using LabView. It would be a simple extension to program flight patterns for the lifter, i.e. make its height follow a signal such as a sinusoid.

Fig. 6.— Induced voltage at base as a function of lifter height

To try to explain our observed relationship between the lifter’s height and the induced voltage at the board, we numerically modeled the lifter’s electrode setup and calculated the potential around the lifter. Figure 7 shows the solution to Laplace’s equation in 2d, calculated using the Successive Over-Relation finite difference method. The boundary conditions consist of a single grid point held at 25.2 kV and a series of grid points below it held at ground, inside a 1 m box held at ground. We see that if we assume that the room, 50 cm away, is held near ground (realistic considering the proximity of surrounding cabinets, etc. to our lifter setup), then it is the HV line that dominates the surrounding potential field. Figure 8 shows the potential as a function of distance directly above or below the electrodes; we see that past a distance of 10 cm below the electrodes, the nearby grounds overwhelm the dipole field, and the voltage begins to drop off as a -2 power law in distance. We note, however, that the restriction to 2 dimensions could have a drastic effect on the values of the potentials we measure: in 3d the harmonic solutions to Laplace’s equation fall off faster than the 2d case.

We then decided to see what potentials to expect if we ignored the grounding skirt. We treated the HV line as a ring of charge, with a circumference equal to the perimeter of our lifter
We measured the capacitance of the lifter to be 2.3 pF, and calculated our expected potential measurements using the equation for the potential along the axis of a charged ring of radius $r = \frac{45}{22}$ cm, taking $Q = C \times V$:

$$P = \frac{1}{4\pi\varepsilon_0} \frac{Q}{\sqrt{r^2 + h^2}}$$

We found that at the heights we measured, the voltage drops off as a -0.9 power law (Figure 9. However, the voltages for both this distribution and the Laplace solution are on the order of kilovolts for the distances we measured. We expect that more complicated boundary conditions, and the effects of the corona on the capacitance and charge on the lifter, must be considered to explain our measurements. However, our data would still serve well for PID feedback calibration.
5. Conclusion

Our goal in this lab was to construct a height-controllable lifter. We constructed a simple yet powerful HV supply using a flyback transformer and driver circuit, capable of producing at least 25 kV with a 50 V input. We also constructed an extremely lightweight lifter, along with a base station giving it essentially free movement along the Z-axis while preventing any other motion or rotation. This setup allowed us to safely yet effectively experiment with different lifter designs and perform a variety of measurements to quantify their performance. Our setup was almost entirely made of components available inside the 111 lab. Only the power MOSFET, potentiometers, one power resistor, and lifter materials were purchased, for a total of under $40 (the flyback was from a condemned CRT courtesy of the Radio Astronomy Laboratory).

We were able to control the thrust produced by the lifter by carefully tuning the frequency of our flyback driver off of the resonance of the flyback. This allowed us to place the lifter at any desired position, enabling us to measure the induced voltage on a conductor placed below the lifter as a function of height. We found a very clear -1.34 power law relation, which although we cannot fully explain theoretically, would serve as an excellent calibrator for a PID feedback mechanism for controlling the lifter’s position in LabView.

In this lab, we extended the skills we gained during the semester to construct a circuit capable of properly driving a flyback transformer. We learned a great deal about the necessary safety precautions involved with high-voltage projects, and how to successfully conduct an experiment while complying with such precautions. This project enabled us build on our knowledge of semiconductors and making physical measurements by designing and performing an experiment to explore the exciting physics behind ionocraft lifters.
REFERENCES


We also acknowledge guidance from Don Orlando. Our driver was based on a design from http://uzzors2k.4hv.org/index.php?page=flybacktransformerdrivers. We borrowed power supplies from Eric Gamliel, and salvaged the flyback from a CRT from the Radio Astronomy Laboratory.