Griffin Sonaty H-8

Designing the Perfect Electroscope – An Engineering Approach

Background

In order to comprehend many of the physical concepts surrounding the topic of electrostatics, a fundamental understanding of electric charge must first be acquired. This is best achieved through tangible manifestations of the properties of electrostatic charge. Any device or instrument that may aid this understanding can greatly influence the overall comprehension of electrostatics. However, mere qualitative observations have a threshold of impact that does not facilitate a comprehensive understanding of the topic. Therefore, some sort of quantitative element must supplement the qualitative approach to electrostatic demonstrations. The following devices are the expressions of this multi-faceted approach to grasping the concepts of electrostatics.

The Engineering Process

Much as the physicists of the 20th century advanced the efficiency and accuracy of instruments for electrostatics demonstrations and measurements, an engineering approach to the problem yields multiple prototypes with varying degrees of precision and effectiveness in displaying electrostatic properties. The first step in finding a solution is to know and understand the problem—to find an instrument or device that accurately displays and quantifies electrostatic properties in the most effective manner (Canright 2008). The next step in this engineering design process is to determine the parameters for the device or instrument to be designed. The design must be simple enough to be homemade with crude elements and resources. It also must palpably display the electrostatic properties at hand. This means that there must be a visual manifestation that shows what is happening. The design must also provide a means to measure the electrostatic interactions in the demonstration. When these parameters are met, the opportunity for an optimal device will be created.

The Spinning Electroscope

As the first parameter is simplicity, the first design began with just that—simplicity. A conducting rod placed on a rotating axle, which is stabilized on a base is one of the simplest designs possible. This design requires very few materials or specified parts, which increases practicality. The design also provides a means for a visual of the electrostatic interaction during the demonstration. The spinning electroscope begins rotating when a negatively charged tube is brought near. This is due to the negative charge in the tube attracting the positive charges within the top of the electroscope, thus driving away the negative charges. The electroscope spins until the induced positive side is closest to the tube. Therefore, if the tube continues to move about the electroscope, it will continue to spin. This electroscope design, however, does not provide a great means to quantify the electrostatic interactions (Hawkins 2011). The calculations for the spin electroscope are as follows:

Point proven. In order to fully satisfy all of the parameters, another design must be implemented.

The Leaf Electroscope

The failure of the spinning electroscope to satisfy the measurement parameter requires a different approach to designing the device. The next simplest design involves two conducting leaves hanging parallel from a conducting rod which is connected to a conducting head, all encased in a glass housing. An insulator is placed between the glass housing and the conducting rod to prevent any distribution of charge entering the housing. When a negatively charged rod is brought near, the leaves deflect due to the rod forcing all of the negative charge to the edges of the leaves, which then repel one another and thus deflect (Hawkins 2011). This means that the electroscope fulfills the parameters of simplicity and having a visual representation of the electrostatic interactions. This electroscope is sensitive to the subtlest electrostatic interactions. The electroscope also offers a crude means of determining the amount of electric charge contained within the charged rod. The distance at which the leaves are deflected may be exploited to find the amount of charge in the rod.

The electric force that the rod exerts on the leaves is given by the mass of the leaves, m, the force of gravity, g, and the deflected distance of the leaves, l, all over the length of the leaves themselves, L, as seen in Eq. (1):

$$F_e = mg\frac{l}{L} \qquad (1)$$

This force may be used to find the electric field of the tube at the leaves by dividing it by the charge of the leaves, Q, as in Eq. (4). Q is found in Eq. (3) by finding the force of the leaves on one another utilizing the distance between the two leaves, r, and the length of the leaves, L, as in Eq. (2):

$$F_l = \frac{mgr}{2L} \qquad (2)$$

$$Q = \sqrt{\frac{F_l r^2}{K}} \qquad (3)$$

$$E = \frac{F_e}{Q} \qquad (4)$$

Where K is the fundamental constant $8.99E^9$ Nm^2/C^2.

Since the rod is long compared to the distance to the leaves, it may be modeled as an infinite line of charge, where the field, E, is defined in Eq. (5). This equation may be solved for linear charge density, λ, Eq. (6), which then may be multiplied by the charged length of the rod, Λ, to find the charge on the rod, q, Eq. (7).

$$E = \frac{\lambda}{2\pi\varepsilon_0 d} \tag{5}$$

$$\lambda = E(2\pi)\varepsilon_0 d \tag{6}$$

$$q = \lambda\Lambda \tag{7}$$

Where ε_0 is the permittivity of free space, 8.85E^{-12} C^2/Nm^2, and d is the distance from the rod to the conducting cap.

This approach gives a quantitative analysis of the charge on the rod, which fully satisfies the parameter for measurement in the device. However, due to the inherent compactness of the leaves, deflection distances, and charge dispersion inside the electroscope, there is much room for inconsistencies in accuracy of the device (Dosso 1962). Therefore, a better solution must be at hand.

The Pith Ball Electroscope

The next logical step in the engineering design process is to improve the effectiveness of the instrument. However, it is not practical to make a giant leaf electroscope, which is the only would-be improvement to that design. Therefore, a new design must be implemented while using the same principles. Suspending two conducting balls on two strings from a hanger seems to fulfill these requirements. Using a similar method as in Eq.'s (1)-(7), the charge of a rod may be found by manipulating the distance deflected by the charged rod of the conducting balls. This method proves to provide a more consistent, accurate depiction of the charge on the rod, since the device is larger than the leaf electroscope (Dosso 1962). This model also incorporates a very visible exhibition of the electrostatic interaction, and is simple enough to build, though it is not shielded from outside forces as well as the leaf electroscope. Yet, there is an even more effective model that may be achieved through applying the same principles.

The Braun Electroscope

In an effort to create the most effective demonstration electroscope, the same principles of visibility and measurability were applied to a new design. Combing the methods of the spinning, leaf, and the pith ball electroscopes, the final design incorporated a somewhat more complex design to yield a simple result that is both very observable as well as computable. The resulting design has a conducting top connected to a fixed conducting rod, which is bound in the middle by a freely rotating conductive second hand rod via a clock pin. All of this is housed inside of a once-was clock. When a negatively charged rod is brought near the top, negative charge is pushed to the edges of the conducting rods, thus repelling one another, leading the freely rotating rod to rotate about the pin. The second-marker that the freely rotating rod reaches may be used to calculate the angle of deflection Eq. (8), which in turn may be calculate to find the distance deflected, l, Eq. (9), which then may be manipulated in the same manner as before (Eq. (1)-(7)) to find the charge on the conducting rod:

$$\theta = \frac{\pi}{30} s \tag{8}$$

Where s is the number of second-marks covered in rotation.

$$l = Rtan\theta \tag{9}$$

Where R is the length of the second hand rod.

Then l may be used to carry out Eq. (1)-(7) to find the charge of the rod. This method proves to be the most accurate as the electroscope is: shielded, large enough distances to measure accurately, observable, and simple to build. The Braun electroscope is the most effective demonstration electroscope from an engineering design perspective. There are more accurate, advanced electroscopes out there, but they are not simple to build, and do not adequately demonstrate the visible nature of electrostatic interactions on a macroscopic level. The design for the Braun electroscope may be improved in the future to maximize accuracy and consistency.

Resources

Canright, Shelley. “Engineering Design Process.” Last modified February 22, 2008, http://www.nasa.gov/audience/foreducators/plantgrowth/reference/Eng_Design_5-12.html.

Dosso, H.W., and R.H. Vidal. “Large Demonstration Electroscope.” *American Journal of Physics.* 30 (1962): 926.

Hawkins, Nehemiah. “Static Electricity.” *Hawkins Electrical Guide*. 1 (2011): 5.

Appendix

Figure 1: Spinning Electroscope

Figure 2: Leaf Electroscope

Figure 3: Pith Ball Electroscope

Figure 4: Braun Electroscope