Simulation of Non-Contact Macroscopic Triboelectric and Tribological Measurement Device

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Abstract—**Tribogenics has created a novel charge measurement device that measures triboelectrically generated charge on a polymer surface. Simultaneous measurement of forces on the polymer band permits study of the tribological properties of the two materials including the dynamic friction. The system under study consists of a polymer band that is pulled across a metal rod. Charge is measured using two metal cantilevers placed above the polymer band. In this paper, we describe simulations of the system. Specifically, we simulate different charge densities on the band and measure the expected deflection of the cantilevers as well as the impact of a second cantilever on the measurement of the charge on the first cantilever. A grounded cup around each metal sphere reduces the charge visible to the cantilever and removes the cross talk between cantilevers. This initial two pixel device could be expanded to multiple pixels for real time mappings of charge on polymer surfaces.**

I. INTRODUCTION

In 2008 Carlos Camara et. al. observed that the triboelectric effect could be used to generate X-rays [1]. This breakthrough resulted in the formation of Tribogenics and the company's first handheld x-ray fluorescence device. Understanding the details of the charge distribution on the surface of dielectrics is key to understanding and controlling X-ray generation via the triboelectric effect.

Commercial devices using faraday cups or electrostatic voltmeters for measuring total charge on the surface of a metal or a dielectric are available,. However, these devices are not capable of measuring the spatial distribution of the charge. Currently, the only commercial devices for measuring the distribution of charges on the surface of a material are the EFM (Electrostatic Force Microscope) and the Kelvin Probe. An EFM is a modified Atomic Force Microscope (AFM) that is tailored for sensitivity to electric fields, while a Kelvin Probe utilizes the difference in work functions combined with fields to measure charge distribution. Both devices, however, are designed for microscopic scale measurements only. We are aware of only two proposals for devices to measure charge distributions on the mm length scale, one by Beardsmore-Rust et. al. [2] and the other by Faircloth and Allen [3]. The former example utilized an array of electrostatic voltmeters to generate a simple charge camera. Faircloth and Allen's system involved scanning a electrostatic voltmeter probe across a surface.

The drawback of both designs is the reliance on electronic devices to directly measure the charge on the surface. Electronic drift is common in these electronics and can be a large source of errors. This contrasts with the EFM or Kelvin Probe which relies on mechanical or material properties to measure the surface charge. These measurements will be more robust over longer times and will not require constant calibration or zeroing of the devices. In this paper, we present the theoretical work performed on a macroscopic version of an EFM. The spatial resolution of the device is investigated as well as the implications of adding additional probes to the measurement to improve the spatial sensitivity of the device.

II. SIMULATION

The simulation is a simplified version of the experimental setup, as seen in Fig. 1. A polymer band is placed on top of a metal rod. The band makes a 90 degree wrap around the rod. Either one or two cantilever rods are positioned above the polymer band. The cantilevers are composed of a brass that is 1 mm wide, 51 mm long and .254 mm thick, a small copper string is attached to the end of the brass beam. At the end of the of the copper is a silver ball 6.35 mm diameter. The brass rod and the silver ball are both grounded. Around the silver ball is a grounded copper tube of diameter 5.16mm OD and 4.76 mm and 1 cm long.

A charge density is applied onto the polymer on the side in contact with the metal rod, which is the side opposite side of the cantilevers. The charge on the polymer would originate from the interaction of the polymer surface and the rod surface while they are in contact. The band is simulated to move from the left of the illustration to the right further exposing charge underneath the cantilevers.

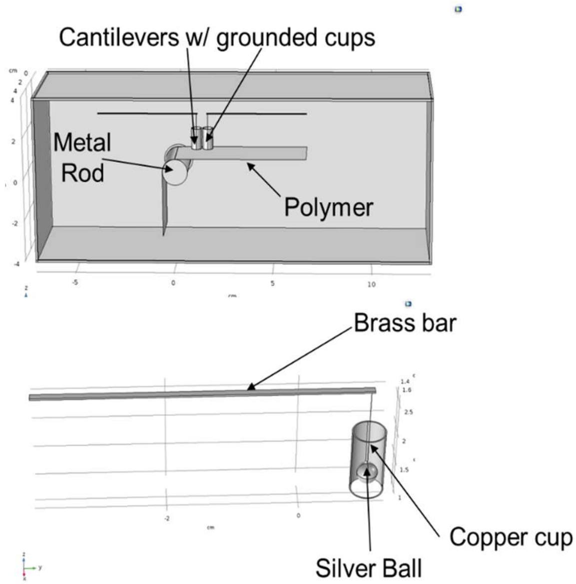

Fig. 1. The experimental setup. A polymer band is simulated to rub on the surface of a polymer. This will result in a buildup of charge on the surface of the polymer. This charge will cause a force to be applied to the cantilevers, which we can measure.

We will investigate the behavior of the system with four different cantilever designs, which are outlined in Fig. 2. The first one is a simple cantilever, as shown in Fig. 1, but where the copper cup, or shield, is removed. We then investigate the impact of the copper shield on the response of the system. A second cantilever, with copper shield, will then be added as illustrated in Fig. 2 in position #1. Finally, the cantilevers will be moved to be side by side as illustrated in Fig. 2 position #2. There are benefits and drawbacks to each of the orientations of the cantilevers. If the cantilevers are placed into position #1, we gain information about the discharge of electrons from the polymer band as a function of time during operation, however we lose and lateral spatial resolution of the charge on the band. However, if we place the cantilevers in position #2 we can gain another pixel, and hence greater lateral spatial resolution of the system, however we will lose any information about how charge might move or leave the band further from the point of separation. We can theoretically solve this problem by adding the ability to move the cantilevers during the operation. This adds further complication and possible noise to the system.

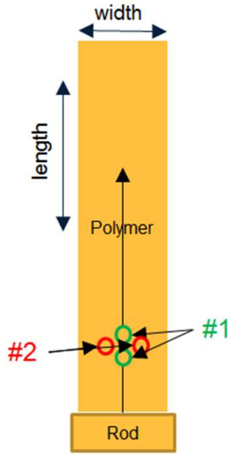

Fig. 2. The possible cantilever positions. There are four different positions investigated in this paper; 1) a single silver sphere with no copper shield around it in the position #1 closest to the rod, 2) the same as 1) but with a copper shield, 3) two cantilevers in position #1 with copper shields and 4) two cantilevers with copper shields in position #2

There are several ways to distribute the charge on the surface of the polymer band, as illustrated in Fig. 3. We will investigate two possible charge density distributions in this study: 1) a square block of charge of varying lengths, along the entire width of the polymer band and 2) a Gaussian dot shown as a contour plot in Fig. 3. The peak charge density for each experiment was kept the same at 0.410 mC/m^2, or2.6x10^{11} electrons/cm^2 of charge, which are numbers reported in the literature [4].

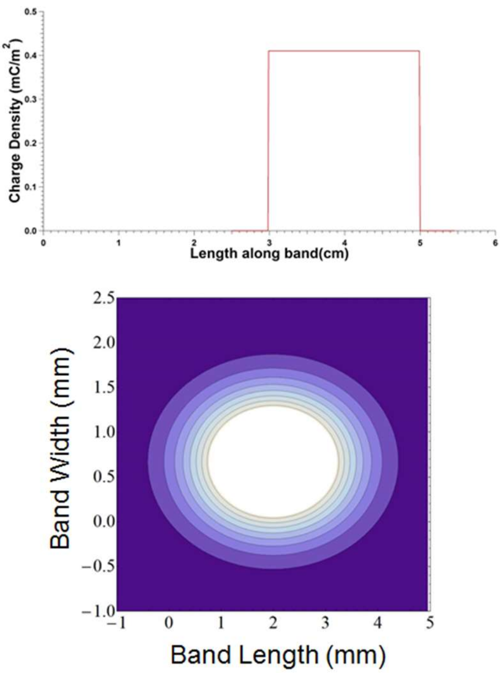

Fig. 3. The two charge densities used. The top charge density, that of a step function. When a second cantilever is introduced into position #2 in Fig.2, then the lower charge density is used, which a Gaussian dot.

III. RESULTS

A. Single Cantilever with and without a shield

First, we examined the response of a single cantilever to a charge patch with uniform density having the same width as the band and its length varied from 1mm to 20mm in length. A typical response of the cantilever can be seen in Fig. 4.

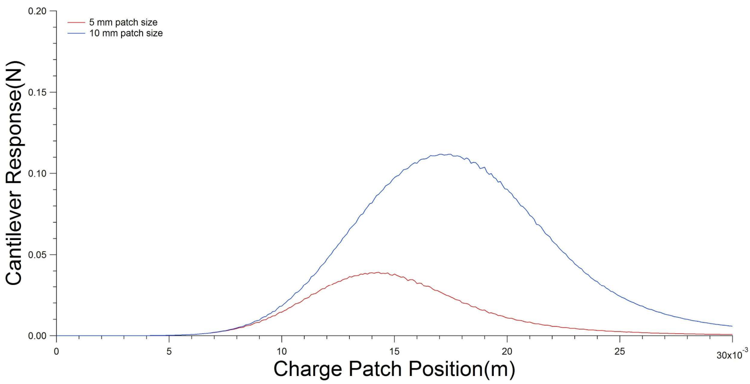

Fig. 4. A response of the single cantilever to two different patch sizes: 5 mm in length and 10 mm in length.

As the charge patched moved underneath the single cantilever we observed peaks in the cantilever response. We can fit a Gaussian, as described in Equation 1, to these peaks and then plot the standard deviation (σ) of the fit as a function of charge patch length, which is illustrated in Fig. 5.

$$f(x) = \frac{A}{\sqrt{2\pi}\sigma} e^{-\frac{(x-x_0)^2}{2\sigma^2}} \tag{1}$$

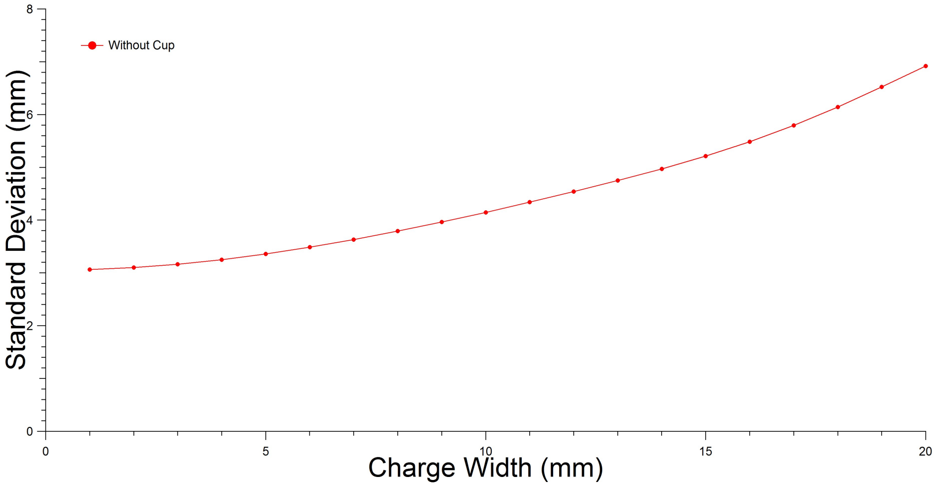

Fig. 5. The peak width of the cantilever response as a function of the charge patch standard deviation. The response monotonically increases with the charge patch standard deviation indicating that once we developed a relationship between the charge patch with and the cantilever's response we can determine the length of a single charge patch.

As the charge patch increases in length, the standard deviation of the cantilever's response increases monotonically. Now we can use the standard deviation of the cantilever's response to measure the spatial dimensions of the charge patch along the length of the band.

Because the force between two charges falls off as $1/r^2$, the cantilever will be impacted by charges from an infinite distance away. This inherently makes the measurement of a charge with a grounded cantilever a nonlocal measurement. A more detailed discussion of the physics behind a grounded sphere and a dielectric can be found in a paper by Bacchetta et. al.[5] . To increase the localization of the measurement a grounded cup or shield is placed around the sphere. We can determine what impact to the measurement of the charged patch this shield will have. Figure 6. illustrates both the standard deviation of the peak of the cantilever's response due to a uniform charge patch both with and without a shield. For small charge patches, the cantilever response with the grounded shield is narrower than it is without the grounded shield while for larger charge patches the response is wider. This is a clear indication of greater localization of the cantilever's response. More work needs to be done, however, to quantify the level of localization that has been achieved and how the geometry of the grounded shield impacts the localization of the cantilever's response.

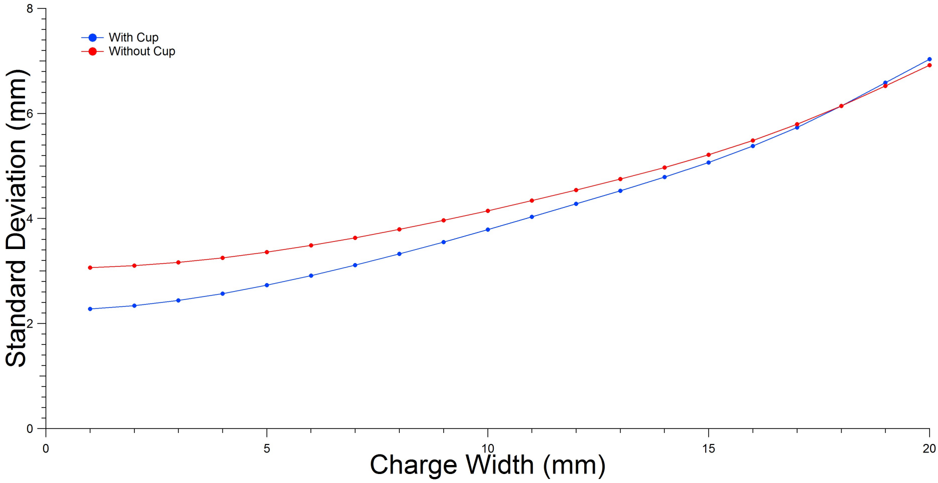

Fig. 6. The response of the cantilever without the grounded cup or shield (red) and with the grounded cup (blue). For smaller charge patches the cantilever response curve has a narrower peak while at 20 mm width the peak width is larger indicating that the shield has the desired effect of increasing the localization of the cantilever's response.

This geometry is similar to those found in EFM's [6]. In those cases, grounded spheres are places at the end of AFM tips. The cantilever is placed above the surface in a non-contact mode and the force on the cantilever due to the charges interactions with the cantilevers are measured. For the case of EFM's, the lack of localization remains, resulting in a blurring of the resulting image. However, in this setup we can add multiple cantilevers. We hope this will have two main advantages over the single cantilever: 1) it will add greater resolution to the device allowing us to achieve resolution in more than one dimension and 2) allowing us to deconvolve the long scale response of the single cantilever providing us with greater spatial resolution. In order to test this idea, we must first examine the impact of the second cantilever on the first. In particular, we must make sure to minimize any cross talk between the two cantilevers.

B. Multiple Cantilever's

Fig. 2 illustrates the position of a second cantilever on the system. Both cantilevers have grounded shield around them to reduce cross talk as well as increase localization of the cantilever's response. For the initial test the cantilevers are placed in position #1 as seen in Fig. 2. The width response of the two cantilevers in position #1 is illustrated in Fig. 7. How the force of the cantilevers changes with the addition of the second cantilever is illustrated in Fig. 8. The force that the charge patch applies to the first cantilever does not change with the addition of the second. This indicates that there is very little impact on the first cantilever due to the addition of a second one. However, there is some impact that needs to be understood.

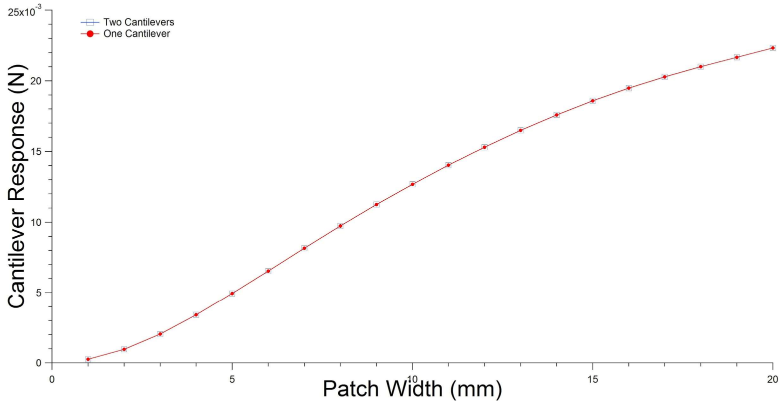

Fig. 8. The magnitude of the force experienced by the cantilever closest to the rod in the case where there is only one cantilever (red) and where there are two cantilevers (blue). There is no change in the magnitude of the force experienced by the cantilever.

Finally, we examined the situation where both cantilevers are next to each other along the width of the polymer band, as seen in Fig. 2 position #2. First, we need to observe how the cantilevers respond to a charge patch in the center along the width of the polymer band. We examined this geometry with two different charge patches , 1) a Gaussian charge patch that has a standard deviation of 0.5mm along the width, but varying the standard deviation along the length from 1mm to 20mm, and 2) a Gaussian charge patch of the same dimensions as 1) except the center of the charge patch is offset to one side by 6 mm on the band. A plot of the peak standard deviation for both cantilevers is illustrated in Fig 9.

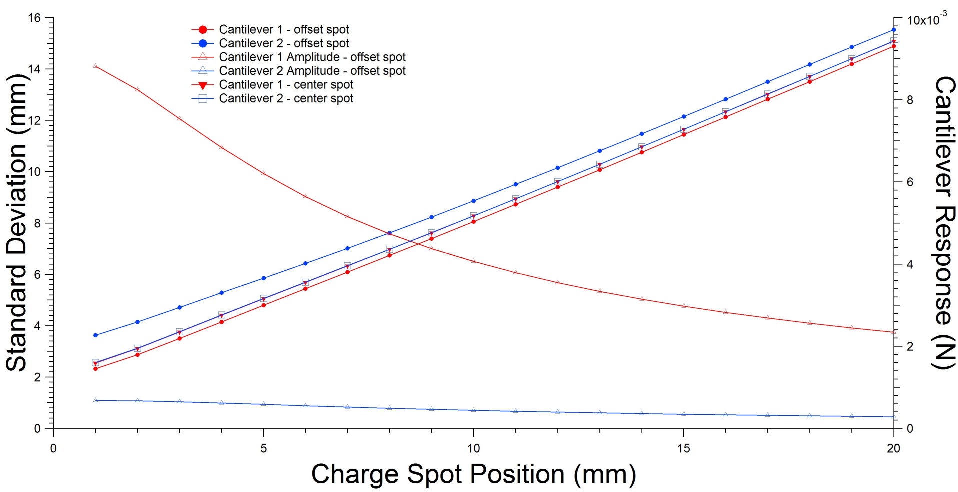

Fig. 9. The red curves are Cantilever 1 and the blue curves are Cantilever 2. The red triangles and blue open squares is the cantilever's response when the charge patch is in the center of the polymer band, while the circles represent the response when the charge patch is offset by 6mm to one side. The red and blue crosses (X) are the amplitude of each cantilever due to the offset charge patch. Although the peak standard deviation does not significantly change because of the offset charge patch, the amplitude of the response is much different.

The cantilevers have similar standard deviation response. The standard deviation of the second cantilever is larger than it is for the first, which is counter intuitive because the standard deviation of the cantilever response should only depend on charge patch dimension along the length of the band and should not be sensitive to the dimension along the standard deviation of the band. In contrast, cantilever 1 has a narrower response than the centered charge patch and cantilever 2. Although more study needs to be done to better understand the relationship between the cantilever response and the charge patch dimensions, what is clear is that the amplitudes of the cantilevers change a great deal in response to the moved charge.

IV. Conclusions

Through simulation, we have examined the theoretical response of a new charge measuring device. It is composed of a polymer material wrapped over a metal rod and pulled to expose charge on the surface of the band that resulted from the triboelectric effect and two metal cantilevers that will experience a force on them in response to the charge. In principle, the cantilevers can be placed in any arbitrary geometry.

The purpose of the device is to measure the spatial distribution of charge on the surface of a polymer. The main difficulty in making that measurement is the infinite range of the electric force. This has the effect of blurring the image of a single cantilever. If more than one cantilever is introduced then a further problem exists of cross talk between the two cantilevers. To solve this a grounded metal cup or shield is added around the sphere at the end of the cantilever bar. We simulated the impact of the cup on the single cantilever and found that it decreased the impact of charges from a distance on the force exerted by the charges on the cantilever. This has the impact of improving the resolution of the device, however the signal will still be blurry

A second cantilever can be added to the system to either 1) measure the charge density on the polymer band at a different point or 2) to add a second dimension to the measurement of the spatial distribution of charge on the polymer band. Ideally this second cantilever would not have any impact on the measurements of the first; however, we show that there is a small impact. More work needs to be done to better understand the influence of the second cantilever on the first.

We also have shown that two cantilevers, placed along the width of the polymer band, are able to see an offset charge spot. There is some shift in the response of the cantilevers because of the offset charge that adds to the uncertainty of the width of the charge patch; however, the shift was much smaller than the change in the amplitude of the cantilevers due to the offset charge. This indicates that the two cantilever in that orientation can be used to measure spatial distribution of charge along the width of the band.

This work shows promise toward creating a high resolution, multipixel, and low drift charge camera. By adding grounded shields around the balls, we minimize the cross talk between pixels, improving resolution and complexity of the device. More work is needed to better address some of these issues.

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