Electromotive Clamp Theory of Operation

Ben Lucas, 11/1/15

The following document outlines a theory of operation governing the operation and design of an electromotive suction device whose primary purpose is to effectively clamp itself onto various surfaces. This work draws from the results of empirical investigations of such devices and aims to present a conceptual framework to order these observations.

Overview:
In its most basic form, an electromotive clamp is formed when two electrodes oriented in the same plane what are connected to the terminals of a high voltage power supply. (See Figure 1). When the plane of this device is placed in proximity to a dielectric material, it induces an electromotive force between the electrodes and the material.

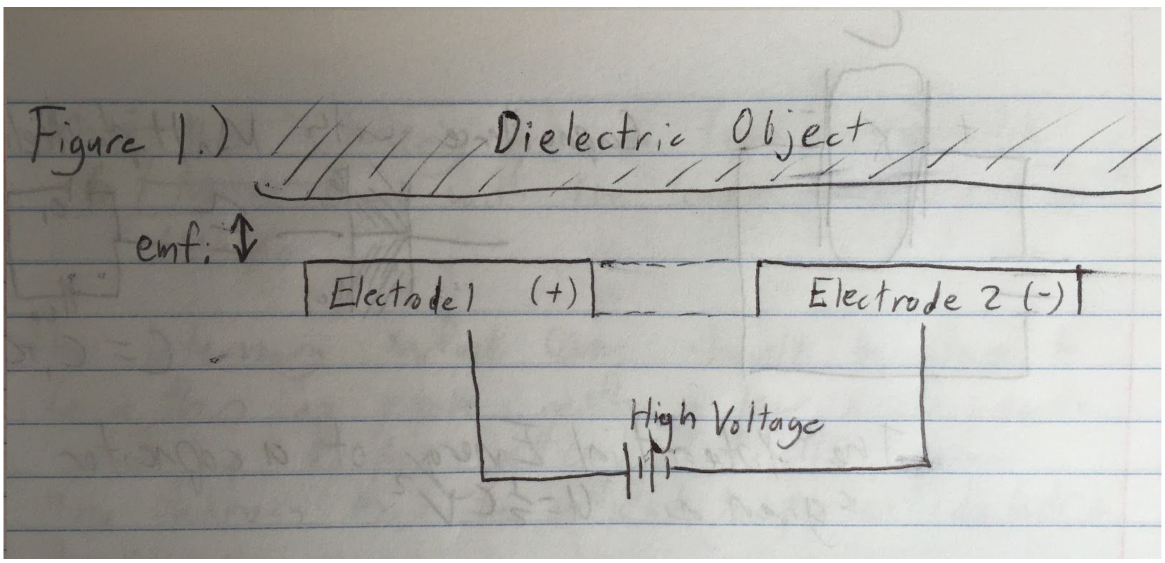


Figure 1: Graphical Illustration of Electromotive clamp

At the fundamental level, the mechanism of the effect can be understood to be the consequence of the electrical polarization of a dielectric material when it is in the presence of an electric field. When a dielectric material is placed inside an electric field, its molecules polarize very slightly and this induces a net charge on its surface that it opposite to the polarity of nearest electrode. The opposing charges of the electrode and the dielectric are attracted to one another and pull the dielectric toward the electrodes. (See Figure 2)

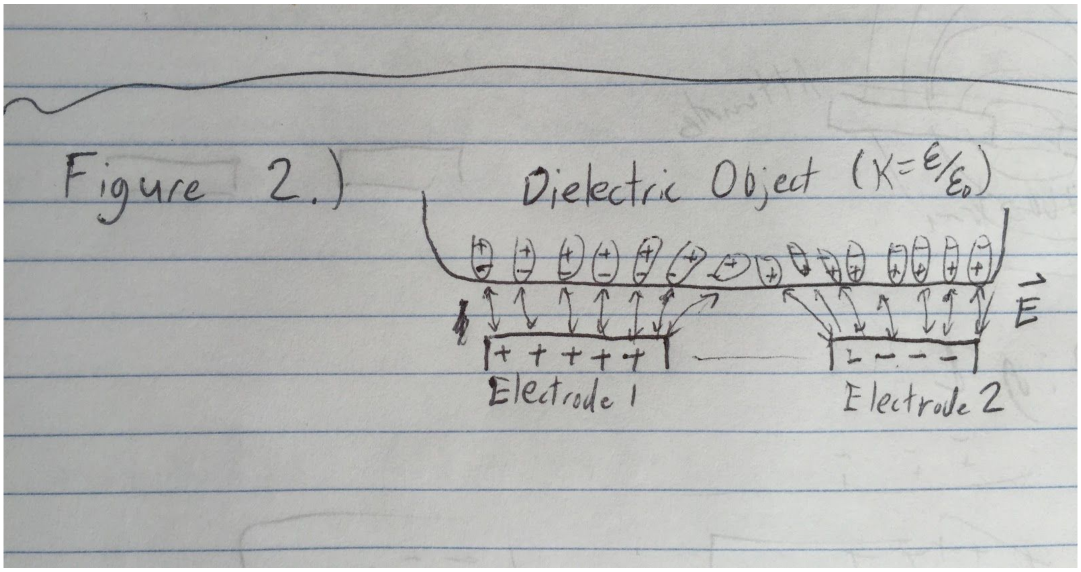


Figure 2: An illustration of the basic physical mechanism of the electromotive attraction.

The magnitude of the induced polarization of the dielectric, and hence the magnitude of effect is given by the dielectric constant of the clamp material. This understanding allows for a much more concise theoretical treatment of the effect which is outlined below.

At a high level, the electromotive clamp can be thought of as a capacitor with variable capacitance. When a voltage is run across a capacitor, the capacitor stores a potential energy *U* given by the following equation:

$$U = \frac{1}{2}CV^2 \qquad \text{(Eq 1)}$$

Here *C* corresponds to the Capacitance which is a function of the geometry of the electrodes and the surrounding dielectric materials, and *V* is the applied voltage.
When the capacitance changes by ΔC, the total energy of the system changes, and conservation of energy implies that work must be done to achieve this. This work is given by the following equation:

$$W = \Delta U = \frac{1}{2}(\Delta C)V^2 \qquad \text{(Eq 2)}$$

In in the case of the electromotive clamp, the capacitance of the system is changed by removing the device from the surface of a wall with dielectric constant κ_{wall}, and replacing this material with air, of dielectric constant ($\kappa_{air} \approx 1$). The magnitude of this change can be understood in terms of a equivalent circuit illustrated below in figure 3:

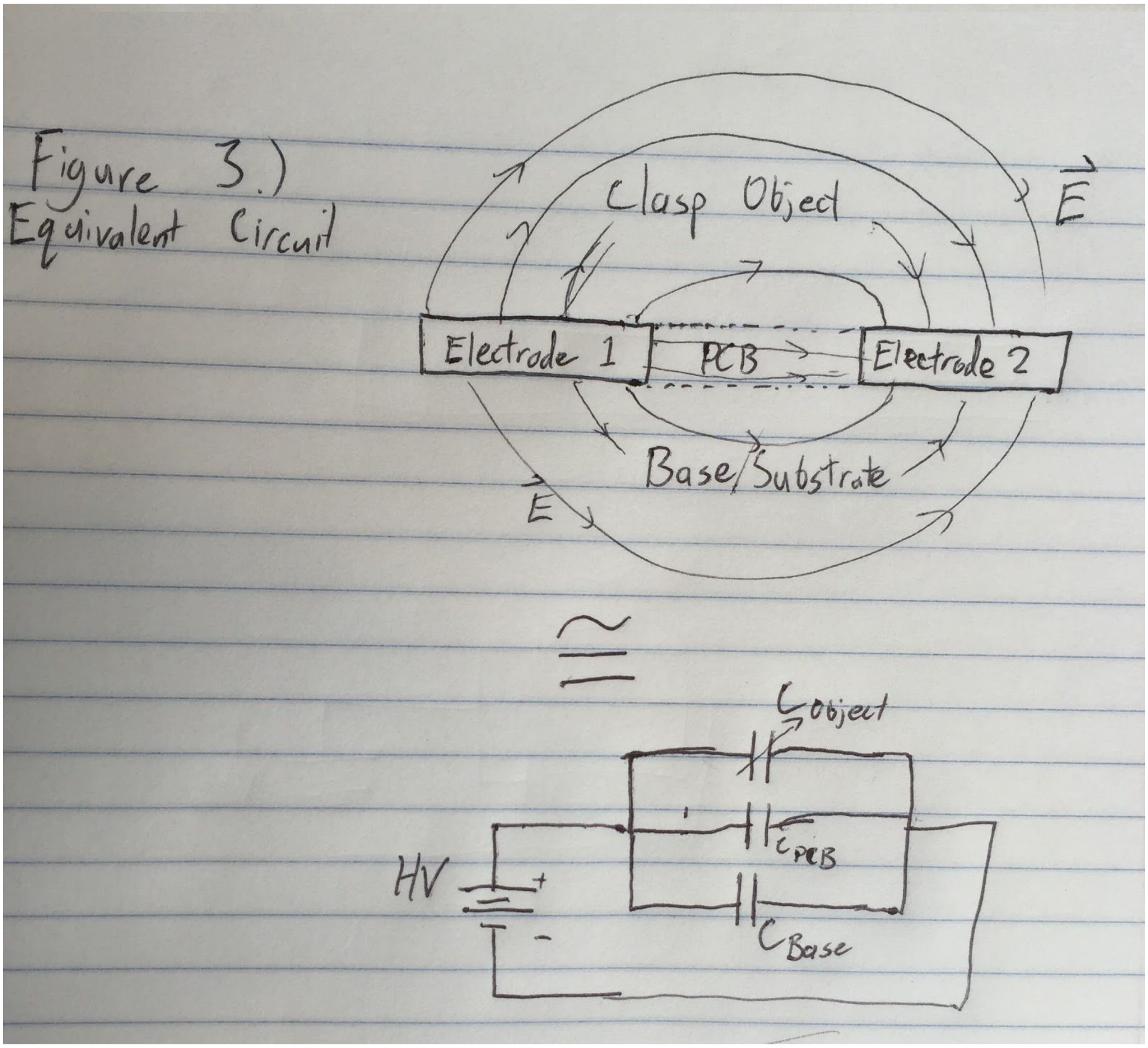


Figure 3 illustrates the electrical forces in the system and outlines an equivalent circuit. It should be noted that this model is a slight simplification of the actual system since there is a thin layer of dielectric material covering the electrodes. This feature has been ignored for simplicity since it does not substantially alter the mechanism of effect. This element will however have practical design implications which will be discussed later.

Since the capacitors are acting in parallel, the capacitance of the electromotive clamp can be expressed as a simple sum:

$$C = C_{base} + C_{pcb} + C_{Object} \quad \text{(Eq 3)}$$

Realistically, the PCB adds a negligible, amount to the capacitance, while the presence of a thin film would add a substantial contribution to the capacitance. Thus if we make the approximation that the protective dielectric layer acts as a series capacitor along with the clamp object, then the Capacitance of the system is Given as:

$$C = C_{base} + 1/(1/C_{film} + 1/C_{Object}) \quad \text{(Eq 4)}$$

In the case of a small film this equation approximates a simple sum of the capacitance of the system, however a thin film will severely reduce the effect of a clamp object on the overall capacitance of the system.

In either case, given equation 3 or 4, the crucial ΔC term of equation 2 reduces to ΔC_{Object}. This result, combined with equation 2 leads to the conclusion that the force *F* exerted by the system is given by the following relationship:

$$F = -\Delta U = constant \cdot \Delta C_{Object} \quad \text{(Eq 5)}$$

In operation, the capacitance of the system is only changed when the dielectric is changed due to the presence or absence of the clamp object, so

$$F = constant \cdot (\kappa_{wall} - \kappa_{air})V^2 \quad \text{(Eq 6)}$$

Here *constant* is a proportionality constant, and V is the applied voltage. In practice, the proportionality constant is related to the capacitance of the system C_{System} ,which is a parameter of the geometric configuration of the electrodes.
For a finite system, closed form representations of C_{System} are not generally available, and this shall be treated as a black-box constant parameter for the time being, however this will factor into system optimizations, which will be discussed in more detail later.
There are two key implications of equation 6. First the effect is sensitive to the dielectric strength of the the material, and materials such as glass or wood will have more adhesive strength than plastics. Second, the greatest increases in the strength of the effect results from changes in voltage. This however is limited by the difficulties of operating a system a voltages above 1kV since issues of arcing and dielectric breakdown come into play. This will be the subject of further discussion.

Discussion on Design Optimizations:
Voltage:
As the above theoretical treatment indicates, a high voltage is the most effective way to increase the strength of the effect. The prototype unit, for example, required 5000 Volts to support a mass of ~ 300g. The simplest way to increase the effect would be to simply increase the voltage. Using the same material configuration, it would then be possible to increase the force to support an object of ~25 lbs by applying a voltage of 30,000 Volts. This, however, presents a number of design challenges pertaining to the application of high voltage which are discussed in detail below.

In general the use of voltages above ~ 1kV result in a number of design challenges relating to the possibility of arcing and dielectric breakdown. These can occur both on short term time scales (t<1 second) term breakdowns and on long term time scales (t>1 day). It should be noted that dielectric breakdowns are non-linear effects and difficult to predict theoretically. Parameters like humidity, dust and system geometry can have large effects which are highly variable. Consequently the following treatment is imprecise in its nature.

In small time scales, the use of high voltage requires adequate spacing and insulation. This will mainly effect the spacing and shaping of the electrodes as well as the surrounding insulators. On longer time scales, the high voltage can result in the potential for random and catastrophic failure. As the materials fatigue and unwanted space-charge buildup in surrounding insulators overtime can result in surface flashovers and the formation of conducting channels that will short out the device rendering it useless. These have not been tested for and it is unknown whether this will be an issue for a future device.

An additional issue with high voltages lies in electrical arcing through air. The dielectric breakdown strength of air is ~30 kV/cm, and this figure will decrease with high humidity and dust, or in the presence of metallic objects with sharp edges. The creation of plasmas by the device can be dangerous for electronics and may hamper the overall effectiveness of the electromotive clamp.
It should be noted that ionization of the air and intervening media was observed to be a problem at 5kV for the known standard device. This since this resulting in a crackling sound from the plasma ionization coming from the device. This feature will limit several applications such as sound, and can only be effectively mitigated by diminishing the overall magnitude of the electromotive force.

System Capacitance
Beyond the use of voltage, equation 6 implies that the capacitance of the system influences the magnitude of the effect. Although closed form analytic solutions are possible for simplified configurations with infinitely wide electrodes, there does not exist a precise mathematical relationship between the electrode configuration and capacitance for finite systems. This would require either theoretical modelling, or simple empirical testing of the width and spacing between electrodes. It should be noted that due to the possibility of dielectric breakdowns, empirical testing is more likely a more effective mode of optimization, since the electrode spacing is limited by the dielectric strength of the intervening materials. For this reason, it should be noted that electrodes with rounded edges and some thickness are superior than perfectly flat electrodes with sharp corners.
The key to increasing the capacitance above the plane of the electrodes lies in creating a large area with a small spacing between the electrodes. This is best done by smoothing winding the electrodes around each other. The electrodes of the prototype clamp follow this design paradigm and are a good starting point for future. An example of these design guidelines are illustrated in figure 4 in the Appendix.

A final feature of the capacitance of the system is the presence of a thin layer of dielectric material separating the electrodes from the clamping object. As a general rule, any material between the electrodes and the clamping object will reduce the magnitude of the electromotive force between them. The reduction will be a function of the thickness of this layer as well as its dielectric constant. Thus a thin material with low κ is ideal for this element. In practice, some degree of thickness is required for safety and to prevent arcing between the electrodes and various metal objects in the environment. The necessary thickness is thus an empirical question whose exact value is a function of the applied voltage and the possible use cases. As design suggestion, a thin (<10 mil) material with a low dielectric constant and high coefficient of friction like silicone rubber or urethane would be ideally suited for this piece of the device.

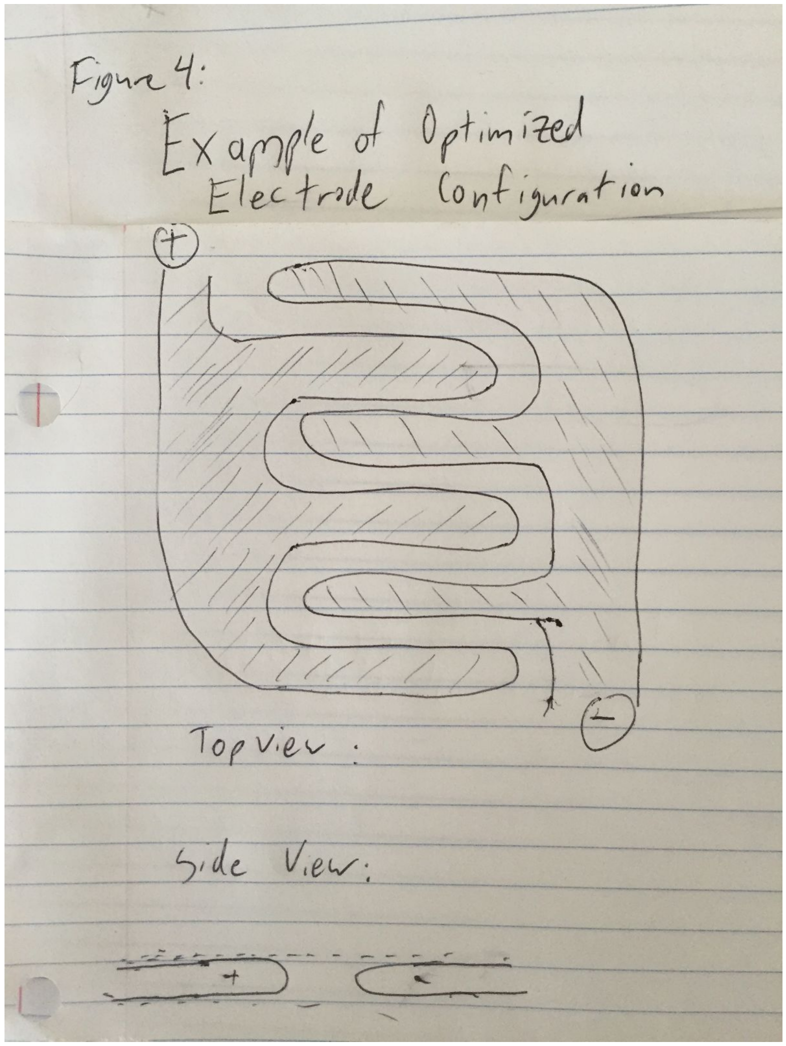
Application Notes:

It was seen that a ~ 285g unit was able to stick to a wood surface with the force derived from a 5kV power supply. For the sake of an estimate this would imply that the device can support ~ 500g of weight. As equation 6 suggests, it is possible to increase this force by either increasing the capacitive area of the the device or by increasing the voltage. As a possible application, consider the use of four such sample pads to support a human of ~150 lbs. Since the person must move, let us suppose that 3 pads must be in contact at a given time. Given that one pad can support ~500 g, three pads can support 1.5kG ~ 3.3 lbs. Thus each pad would require about 45x more force to support the weight of person. This could be done by increasing the voltage on each pad by a factor of ~7 to 35kV per pad. This does not take into account potential challenges in high voltage engineering that might arise with this much voltage.

Beyond this, an interesting application may lie in the use of electromotive force to maneuver a small reconnaissance robot up walls. If we assume that such a robot would be equipped with ~ 10lbs or 4 Kg of sensors, it would only be necessary to increase the total voltage to ~ 15kV or to ~10kV with a larger area. This may have potential military application, since the effect would be robust to the presence of dust on the surface of walls, which is common in desert countries.

Appendix:

Figure 4.) Sketch of a hypothetical optimum electrode configuration:



Summary of Experimental Observations:

All results are from testing of various grid patterns at 1kV.

The presumed set up for the apparatus consisted of a high voltage power supply connected to two electrodes covered by a polymer sheet. It was found that a styrofoam test weight had no observable adhesion to the apparatus.

Using an exposed set of electrodes connected to a 1kV high voltage did exert an attractive force on polymer and paper samples on the order of ~10^-2 Newtons. Since this force is small, measurements are largely subjective and based on the perception of force on the hand.

Observations:

Higher Voltage resulted in higher attractive force, however this led to arcing across the closest electrodes at ~ 2.3kV.

The attractive force exists when test materials are between two oppositely charged electrodes even when there is no contact between the test material and the copper electrodes.

The width of the copper electrodes did not have a discernible effect on the magnitude of the attractive force.

The spacing did have an effect on the magnitude of the attractive force, with higher electrode spacing densities yielding greater attractive forces.
The hexagonal grid is effective. In general, was hard to discern which of the grid formations was the most effective, however high electrode spacing density did correlate with attractive force in all instances.

The thickness of the test material did not appear to effect the magnitude of the attractive force.

The proximity of the material to the electrodes is significant, with a minor increase in distance causing a substantial drop off in force.

In general Paper seems to have had the strongest attraction to the apparatus, though it is hard to compare materials. Since the proximity of the material to the electrodes is significant, the effect of material properties and thickness on the rigidity of a test sample has a substantial impact on the ability of that sample to conform to the surface of the apparatus and thus achieve the maximum attractive force.

Higher current does seem to be related to higher forces, though this is most likely incidental to the actual effect and more a result of the fact that higher grid densities have higher force and also more contact points for conduction

Using a standard Voltage of 1kV, it was found that the current ranged from ~10 to 100 uAmps giving a total power of <0.1W. A realistic estimate of the average power consumption of of paper was ~ 10-50 mW.

Static electricity does appear to effect the attraction between a test material and the apparatus, however, this effect is most likely incidental to the effect that we are studying. This does result in a source of error to any prospective measurements, and this parameter should be controlled for in high resolution materials testing.

It is my conjecture that the effect is the result of the change in energy of the net capacitance between the electrodes as a result of the introduction of a dielectric material into the intervening electric field. According to this theory the effect is simply a matter of the change in total energy of the capacitance between the electrodes with and without the test material on their surface.

Here the potential energy of a capacitor is given by the expression:
U = (1/2)*C*V^2

According to this theory, the largest gain is found by increasing voltage.
The capacitor can be thought of as a network of three capacitors in parallel with one corresponding to the capacitance of the substrate/base of the electrodes (wood), one corresponding to the polymer that the copper is printed on in the pcb, and the final, and most critical one corresponding to the capacitance of the dielectric test material.

According to this theory, the best design is one that maximizes the capacitance between the two electrodes through the test material. I have proposed that a spiral does this, however the actual proportion of wire to spacing has yet to be determined. Furthermore, there are other spacing schemes which may have similar capacitance.

As an additional note, the strength of the effect with be primarily a function of the dielectric of the test material. This can be verified once a suitable test rig has been assembled to make precision measurements of the forces involved.

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