Non-contact surface charge/voltage measurements
Capacitive probe - principle of operation

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Abstract The vibrating capacitor method is a very well known and effective method for investigations of surface electric potentials. This paper gives a brief description of the principle of operation of the vibrating capacitor probe.

1 Introduction

A capacitive probe is one of the most popular devices for surface charge and surface potential measurements. Its principle of operation has been known for a very long time. This technique was proposed by Lord Kelvin [1] in 1898. Since that time many improvements and modifications were introduced to the original Kelvin's construction, leading to development of more accurate and easier-to-use devices [2–10]. Capacitive probe allows for non-contact and non-destructive examination of the surface charges and/or voltages. The principle of operation has its origin in the very basic equation defining capacitance of a capacitor:

$$C = \frac{Q}{U} \quad [F], \tag{1}$$

where:

C is capacitance of a capacitor,

Q is an electric charge accumulated by the capacitor,

U is the voltage between electrodes of the capacitor.

One of the simplest constructions of a capacitor consists of two flat and parallel conductive plates. The capacitance of such a structure depends on the surface area of the planes, the length of the gap separating the plates and the nature of the medium between them. When the voltage U is applied to such a device, the amount of charge stored in it is directly proportional to the voltage. This approach is valid assuming that the electric field between the electrodes of the capacitor is homogeneous and uniform. The capacitance of the parallel-plate capacitor can be expressed as:

$$C = \frac{\epsilon\epsilon_0 A}{D} \quad [F], \tag{2}$$

where:

ϵ is the relative electric permittivity of the material between the electrodes, $\epsilon \approx 1$ for air,

ϵ_0 is the electric permittivity of vacuum, $\epsilon = 8.85 \cdot 10^{-12}$ [F/m].

The same configuration is used in the capacitive probe: the capacitance is created by the probe and the plane under test (Figure 1).

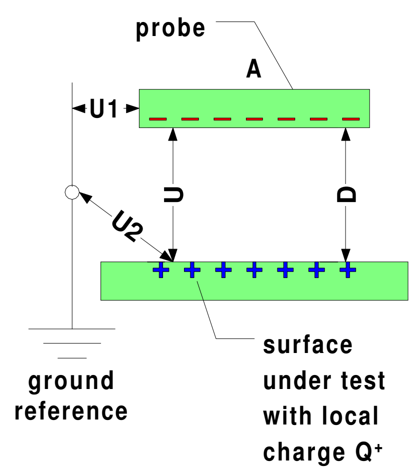

Figure 1: Parallel-plate capacitor.

Voltage U1 corresponds to a difference of potentials between the probe and the ground (earth) reference and U2 is the voltage between the charged plane and ground. The voltage U between electrodes of the capacitor is then equal to

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|U1-U2|. Assume for a moment that the probe is grounded (so that U1=0 and U=U2). The charge on the tested surface can be then calculated as:

$$Q = U \cdot \frac{\epsilon\epsilon_0 A}{D} \quad [F]. \tag{3}$$

As long as it is possible to determine the voltage U and U1, the charge on the tested surface can be calculated.

Example 1: Assume that there exists a localized, constant electric charge on the tested surface and it is equal to $3.5 \cdot 10^{-14}$ Coulombs ([C]). Since the charge is constant, the voltage U2 also does not change. Assume further that the probe surface area is 20 [mm^2] and the air gap ($\epsilon \approx 1$) between the probe and the tested plane is 5 [mm]. At this moment the probe is at the fixed voltage level U1 in reference to ground. Under these conditions the voltage U between probe and surface is:

$$\begin{aligned} U &= |U1\text{-}U2| = \frac{D \cdot Q}{\epsilon\epsilon_0 A} = \\ &= \frac{5 \cdot 10^{-3} \cdot 3.5 \cdot 10^{-14}}{1 \cdot 8.85 \cdot 10^{-12} \cdot 20 \cdot 10^{-6}} = \\ &= 1[V] \end{aligned}$$

Notice that if the distance D increases to 10 [mm], the voltage between electrodes will raise to 2 [V]. In order to keep the voltage U at 1 [V] level it would be necessary to adjust U1, since U2 is constant. This can be done by removing some of the electric charge ($1.75 \cdot 10^{-14}$ [C], to be exact) from the probe.

This observation leads to the principle of operation of the Kelvin probe: any change of the distance between electrodes during the time interval dt requires certain amount of electric charge dQ to be delivered to or taken away from the probe so the voltage U can remain constant. Plugging all that information into equation 3 leads to the following expression:

$$\begin{aligned} \frac{dQ}{dt} &= U \cdot \epsilon\epsilon_0 A \cdot \frac{d}{dt}\left(\frac{1}{D(t)}\right) = \\ &= U \cdot \epsilon\epsilon_0 A \cdot \frac{\frac{-dD(t)}{dt}}{[D_0 + D_1(t)]^2} \end{aligned} \tag{4}$$

where $D = D(t) = D_0 + D_1(t)$ becomes time-dependent and is comprised of 2 components:

- a constant $D(0)$ representing the separation between electrodes before change of the distance,

- a function $D_1(t)$ describing changes of the distance in time.

The expression $\frac{dQ}{dt}$ actually defines an electric current I flowing either from or to the probe when the distance D is being changed ($I = \frac{dQ}{dt}$). Therefore it is possible to find out the voltage between the probe and the surface under test simply by measuring the current I and the distance D:

$$U = \text{-}I \cdot \frac{[D_0 + D_1(t)]^2}{\left(\frac{dD_1(t)}{dt}\right)\epsilon\epsilon_0 A} \tag{5}$$

Example 2: Considering data from example 1 – the amount of charge transferred from the probe to maintain constant difference of potentials was $1.75 \cdot 10^{-14}$ [C]. Assume that time in which the distance had been changed is 1 [s]. Therefore the current is:

$$\begin{aligned} I &= \frac{dQ}{dt} = \\ &= \frac{1.75 \cdot 10^{-14}}{1} = \\ &= 1.75 \cdot 10^{-14}[A] \end{aligned}$$

It takes a very precise instrumentation to detect such small currents. Notice (equation 4) that when the change of the distance (or speed) $\frac{dD(t)}{dt}$ of the probe increases, the current I also increases. Current will also increase when the probe is being moved closer to the surface and/or when its area A is increased.

Another way of surface potential and/or charge measurement, often called the null method, is to

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apply an external voltage U1 to the probe. This voltage can be adjusted bringing the potential difference U to the desired value. If U1=U2 the voltage U will be equal to 0. There will be no current flowing to or from the probe. In other words, whenever during the movement of the probe the current becomes zero, the potential of the probe is equal to the potential of the tested surface.

2 Vibrating capacitive probe

In 1932 Zisman [7] introduced the vibrating Kelvin probe. The probe vibrates in the direction perpendicular to the tested surface and the current flowing to and from the probe changes proportionally to the amplitude and frequency of that vibration.

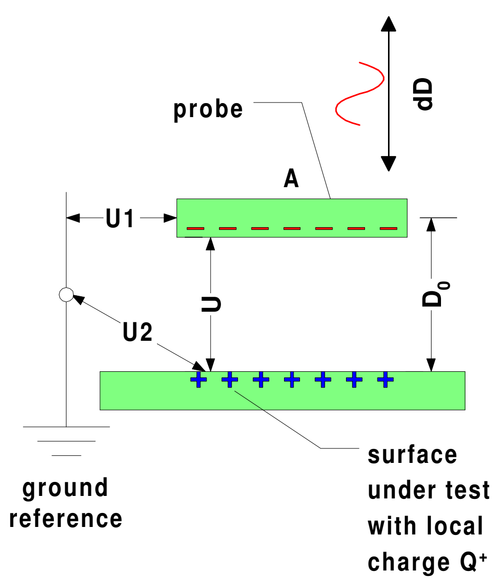

Figure 2: Vibrating capacitive probe.

If the motion of the probe is sinusoidal (Figure 2), then the distance D is equal to:

$$D = D_0 + D_1 \cdot \sin(\omega t) \quad [m], \tag{6}$$

D_1 is the amplitude of vibrations [m],

ω is the circular frequency of vibrations, $\omega = 2\pi f$ [rad/s], where f is a frequency in [Hz].

The capacitance of the plate-probe configuration is then:

$$C = \frac{\epsilon\epsilon_0 A}{D_0 + D_1 \cdot \sin(\omega t)} \tag{7}$$

The current can be determined as:

$$\begin{aligned} I &= U \cdot \frac{dC}{dt} \\ &= U \cdot \frac{d}{dt}\left(\frac{\epsilon\epsilon_0 A}{D_0 + D_1 \cdot \sin(\omega t)}\right) = \\ &= -U \cdot \epsilon\epsilon_0 A \cdot \frac{D_1 \omega \cos(\omega t)}{[D_0 + D_1 \sin(\omega t)]^2} \end{aligned} \tag{8}$$

In order to nullify that current the voltage U has to be brought to zero. In this case the probe-to-ground voltage U1 will be equal to the voltage on the surface U2. The crucial factor here is proper detection of the current, so the voltage U1 can be appropriately adjusted. A broad variety of designs for current detection circuitry was proposed in order to improve the quality of surface charge and potential readings [11–20].

2.1 Probe vibrating in the direction parallel to the surface

Among many different constructions of the vibrating probes, there is a group of devices where the surface of the probe is moving in the direction parallel to the tested surface (Figure 3).

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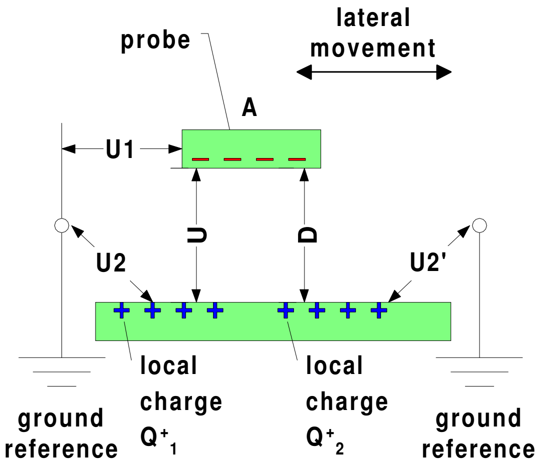
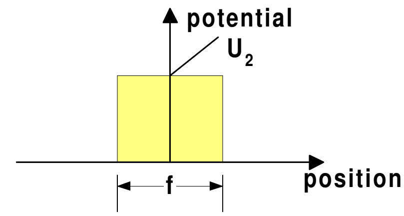


Figure 3: Lateral probe.

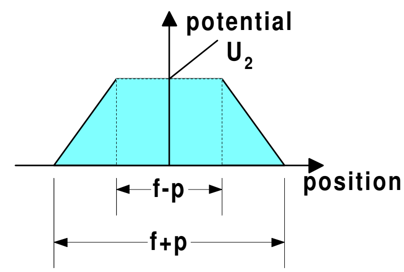
If the air gap distance D is kept constant while the probe moves laterally across the tested area, the capacitance C of the whole configuration remains constant but the voltage U may change due to variations in surface potential or charge. Electric current detected during that voltage change dU is expressed as:

$$I = \frac{dU}{dt} \cdot C \tag{9}$$

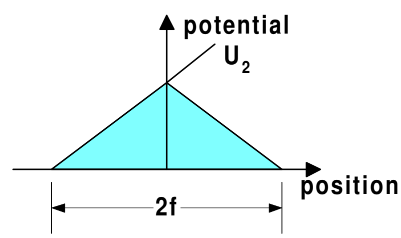
This technique is called the induction or scanning mode [21]. Notice that, as in the case of probe vibrating in the direction perpendicular to the surface, the faster the probe is moved along the surface the bigger the detected current is. One of the drawbacks of this method is that probes working in the scanning regime tend to average the surface potential underneath. For example, consider Figure 4. With a diameter of the scanning probe p smaller than the size of the charged area f, the probe will register the distribution of potential as in Figure 4(b).If probe diameter is equal to the diameter of the charged area, the probe will show the distribution as in Figure 4(c), and, when the probe diameter is bigger than the charged area diameter, the registered distribution will be as in Figure 4(d).



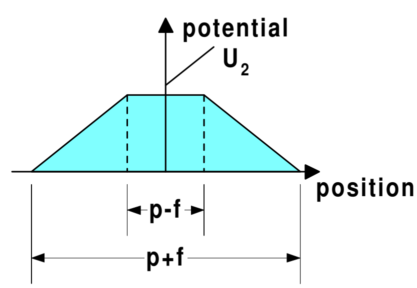
(a) Potential distribution.



(b) Detected potential distribution for f>p.



(c) Detected potential distribution for f=p.



(d) Detected potential distribution for f<p.

Figure 4: Example potential distribution [21].

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Scanning mode probe was a predecessor of the technique where the probe is vibrated in the direction parallel to the surface (Figure 5) [22]. The differential voltage dU is a difference between the surface potential U2 and the reference potential U2'.

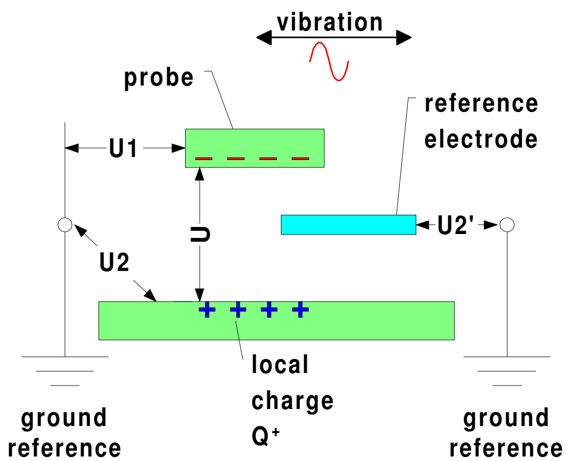

Figure 5: Lateral vibrating probe.

3 Limitations

There exist many factors that determine the sensitivity and accuracy of the Kelvin probe. Influence of some of them can be limited by proper probe design, shielding, use of special electronic circuitry, etc. The following list describes the most important ones:

Noise The Kelvin technique is very sensitive to electromagnetic and mechanical noises (i.e. microphonic signals caused by vibrating wires and insulators, triboelectric and piezoelectric effects, external electric fields, charge build-up on the probe) [23]. During the measurement the intention is to nullify the current flowing due to changes in the probe-to-surface distance (or due to changes in the surface potential levels for the laterally moving probe). When that minimum is reached, the signal-to-noise ratio is also at its minimum. At this moment any noise can cause a significant offset in the detected current values. Noise problems can be partially avoided by employing proper filtering and shielding techniques.

Stray capacitance Capacitive probe responds not only to the capacitive coupling to the tested surface, but also to all distributed capacitances of the surrounding environment: wires, mechanical parts, etc. This additional capacitance is also modulated during the movement of the vibrating probe. This effect can be reduced by appropriate shielding [4, 24–26].

Spacing problems Theoretically the voltage bias U1 applied to the probe in order to nullify the current should be independent of the geometry of the capacitor (if U1=U2 then U=0 and automatically I=0, equation 4) [27, 28]. In practice it varies with the spacing due to such effect as:

- nonparallel probe and tested area surfaces,
- edge effects and nonhomogeneous electric field between probe and the test surface,
- capacitive coupling,
- nonuniform distribution of the charges on the tested surface (which leads to a problem of the probe resolution, described below).

3.1 Resolution

In order to achieve a good resolution of the probe a small probe surface is required. It is also a good idea to get as close to the tested surface as possible. Figure 6(a) shows the surface area of the test plane "seen" by the small probe, Figure

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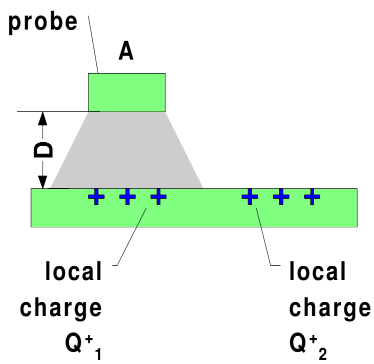
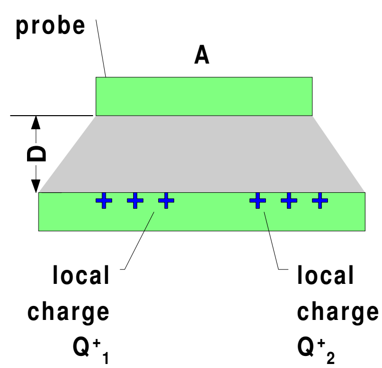
6(b) presents the area recognized by the probe of much larger surface. The latter one does detect higher surface potential because it takes into account the neighboring residual charges Q_2^+.



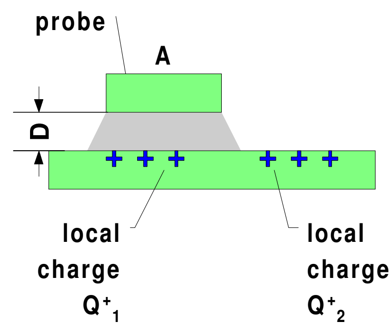
(a) Small probe area



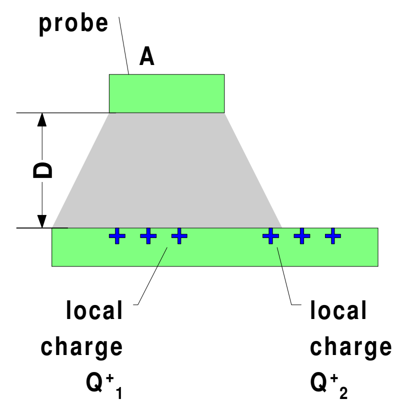
(b) Large probe area

Figure 6: Resolution and surface area of the probe.

In Figure 7 the influence of the distance gap between the probe and the tested surface is shown. With the smaller probe-to-surface distance the ability of the probe to detect localized charges increases (Figure 7(a). When the distance is too big, the probe detects also other surface charges present in the vicinity of the probe (Figure 7(b)).



(a) Small distance from the probe to the surface



(b) Large distance from the probe to the surface

Figure 7: Resolution and spacing of the probe.

It becomes apparent then that for greater resolution of the measurement the probe has to be placed as close to the tested surface as possible. Any accidental contact though could likely damage the tested surface and the probe circuitry. Also, whenever high voltages are present, an extreme caution must be exercised to prevent a discharge between the probe and the surface.

4 Conclusions

The capacitive probe is frequently employed as a sensing element in many electrostatic fieldmeters

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and voltmeters. The surface potential and charge measurements can be easily influenced by stray electric fields and capacitive coupling to the surrounding environment. Those unwanted factors can be partially eliminated by choice of proper shielding and current detection techniques. Sensitivity and resolution of the probe depends on the area of the sensing element and probe-to-surface distance.

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