Journal of Electrostatics 96 (2018) 57–63

Contents lists available at ScienceDirect

Journal of Electrostatics

journal homepage: www.elsevier.com/locate/elstat

Comparison of vibrating and fixed Kelvin Probe for non-destructive evaluation

Michael Reznikov[a,*], Maciej Noras[b,**], Matthew Salazar[a]

[a] Physical Optics Corporation, 1845 W. 205th Street, Torrance, CA, 90501, USA
[b] University of North Carolina at Charlotte, 9201 University City Blvd., Charlotte, NC, 28223, USA

ARTICLE INFO

Keywords:
Electrostatic induction
Electrostatic measurements
Space charge
Surface corrosion
Voltage measurement

ABSTRACT

This paper presents a comparative study of surface electrical potential measurement carried out with the classic vibrating Kelvin probe and with the newly designed swing capacitor transducer. Mathematical modeling and experimentation demonstrated that the non-vibrating swing capacitor probe is notably more sensitive (in some instances more than six times) than the vibrating Kelvin probe in cases where space charge is buried under dielectric layers with slow polarization. This provides an advantage in multi-layer structures, for example, to detect and localize corrosion under paint.

1. Introduction

Excluding recent developments in the Kelvin Probe (KP) technique [1], which was stimulated by the availability of atomic force microscopy equipment, classic KP [2] is considered mature and established. The present work is the more detailed presentation of concept and research reported at the 2017 Annual Meeting of the Electrostatics Society of America [3].

Originally, the capacitive probe measurement of surface (Volta) potential was proposed by Lord Kelvin (W. Thomson) [4] as a switching capacitive quadrant electrometer (CQE) utilizing the sampling capacitor and the ground (discharge), as illustrated in Fig. 1.

The CQE consists of a fixed and grounded electrode, which is split on four segments (“quadrants”), and a symmetric (for balance) electrode, which is suspended over the grounded electrode or between two grounded electrodes. While connected in series, the sampling capacitor and the CQE have the same charge. The ponderomotive force rotates the suspended CQE electrodes to minimize the capacitance between them and the fixed electrodes. The rotation stops when the reaction of twisted suspension compensates the torque from the electrostatic force. The established rotation angle is indicated as the angular displacement of the reflected light beam by the mirror, which is attached to the suspension. Thus, the CQE actually works as a capacitor as well as a meter of the charge induced in the capacitive sample holder. To discharge the CQE, it is periodically manually switched to the Earth's ground.

Use of the potentiometer permits implementation of the “zero signal” approach to overcome the non-linearity of measurement, where the electrostatic rotating moment in the varied capacitor is compensated by the mechanical reaction of twisted suspension. Specifically, the biasing voltage of the potentiometer varies until the electrometer shows the “zero” signal. The corresponding biasing voltage is the exact potential difference induced between the sample of material and the reference electrode. Thus, the original KP actually measured the potential difference caused by the static, steady-state induced charge.

To eliminate the time-consuming adjustment of biasing voltage, the vibrating electrode method [5], which is widely used in contemporary vibrating KP (shown in Fig. 2), was invented by W. A. Zisman 34 years later. In this KP, the distance between the probe and the sample material is adjusted to achieve a capacitance, C_p, significantly larger than the capacitance of the probe to the ground, C_G. In fact, the variation of C_p and thus the aggregated capacitance, $(C_p^{-1}+C_G^{-1})^{-1}$, leads to the redistribution of electric charge between these two capacitors (C_p and C_G), which generates the measured signal. The magnitude of the alternating current (AC) signal, created due to the vibration, is proportional to the variation of charge induced in the probe. The compensating biasing voltage is generated by the probe electronics, and it is applied either directly to the probe, as illustrated in Fig. 2, or/and to the electrostatic shield in proximity to the sensing electrode, which then cancels the electric field sensed by the probe (a field-zeroing method [6]).

Such a compensating feedback loop is needed because $C_p(t)$ depends

---

[*] Corresponding author.
[**] Corresponding author.
E-mail addresses: mreznikov@poc.com (M. Reznikov), mnoras@uncc.edu (M. Noras).

https://doi.org/10.1016/j.elstat.2018.09.008
Received 6 August 2018; Received in revised form 24 September 2018; Accepted 27 September 2018

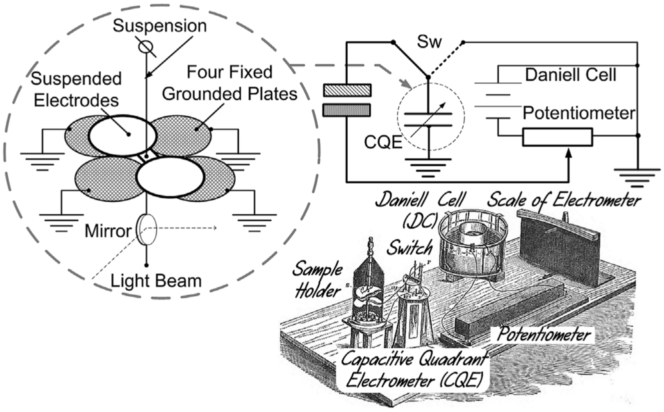

Fig. 1. Lord Kelvin's apparatus circuit diagram and sketch [4].

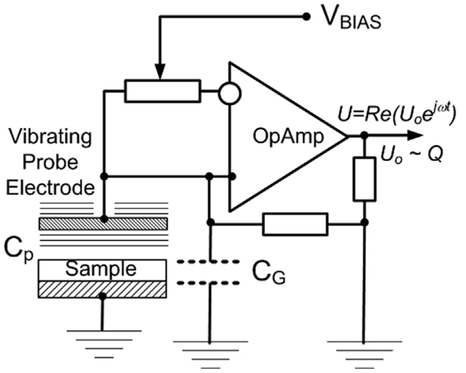

Fig. 2. A simplified circuit diagram of a contemporary Kelvin Probe (KP 6500 from McAllister Technical Services, USA) where the biasing voltage (V_{BIAS}) is applied either to the probe (as shown) or to the sample of material.

nonlinearly on the distance between the probe and sample:

$$C_p(t) = \frac{\varepsilon\varepsilon_0 A}{d_0 + d_1 \cdot \sin(\omega t)}, \tag{1}$$

where ε is the relative electric permittivity of the material between the probe and the surface under testing, $\varepsilon \approx 1$ for air, ε_0 is the electric permittivity of vacuum, A is the surface area of the sensing electrode, d_0 is the distance without the vibration, d_1 is the amplitude, and ω is the frequency of the vibration.

The KP instrumentation is successfully used in multiple applications where measurements are done over clean surfaces of conductive objects and in surface potential measurements of dielectric materials where the capacitance between the probe and the surface of the sample C_p is much greater than the probe to the Earth's ground capacitance, C_G. One of the issues that has not yet been mentioned and addressed is the fact that the polarization dynamics of the C_p dielectric material can affect the results of the KP measurement.

The importance of considering the polarization phenomena during KP measurements becomes apparent in applications such as early detection of corrosion of a metal substrate under a layer of non-conducting paint. Corrosion is possibly the most important factor in the inflation of life-cycle costs of machinery, vehicles, and structures. In this respect, a nondestructive evaluation (NDE) technique is needed to monitor, detect, and report the early stages of corrosion before the damage becomes significant. A recent technical review [7] indicated that the number of publications related to the application of scanning KPs in the corrosion field practically doubled after 2008. For example, the implementation of a high-resolution scanning KP on the base of atomic force microscopy equipment clearly demonstrates the ability of the KP technique to detect the expansion of corrosion from a coating crack [8].

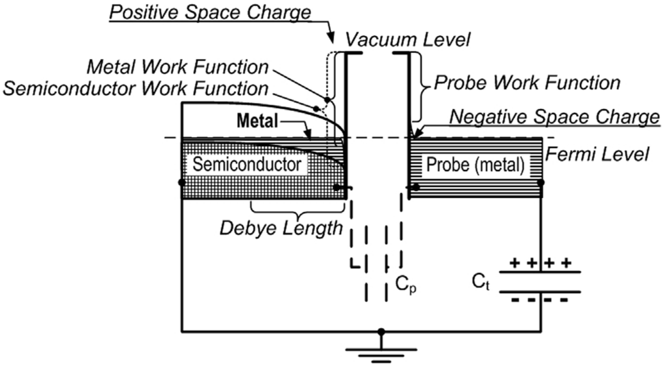

Fig. 3. The space charge formed due to the metal and semiconductor work functions. C_p is the capacitance between the probe and material sample, and C_t is the capacitance of the probe (CQE), in the case of the original Kelvin apparatus) to the Earth's ground.

Thus, the application of the classic vibrating KP in the real NDE world faces two main challenges: the precise following the surface relief is needed to keep a constant distance between the surface and probe, and the effect of the dielectric or low-conductivity surface coating on the measured signal. The work presented below addresses these challenges through the refreshed, if not novel, approach to potential surface measurement.

2. Concept and modeling

2.1. Concept

The electrical potential, measured by the KP over the material's surface, results from the electric field created by the space charge, as illustrated in Fig. 3.

This space charge is located under the material's surface and is formed during the equalization process of electrochemical potential (Fermi energy level) in the material and the probe. The difference between this potential and the electrochemical potential in a vacuum at an infinite distance from the material ("vacuum level") is called the "work function" (the work required for the electron to move from the material to an infinite distance in a vacuum). In the case of a material's clean surface, as shown in Fig. 3, the surface density of the sub-surface space charge is defined only by the difference of work functions, while the distribution of charge with the distance from the surface depends on the concentration of charge carriers in the material. The effective thickness of the space charge layer is characterized through the Debye screening length, but it does not affect the total surface density of the space charge nor the external electric field, which is measured by the KP. However, the time constant τ, which describes temporal development (or variation) of space charge, can affect the electric field and surface potential measurement results:

$$\tau = \frac{\varepsilon\varepsilon_0}{\sigma} = \frac{\varepsilon\varepsilon_0}{qn\mu} \tag{2}$$

where σ is the conductivity of the material under testing, q is the electric charge of a carrier (electron, hole, or ion), n is the concentration, and μ is the mobility of the carriers. In materials with high conductivity (short τ), the frequency of KP vibrations is significantly lower than the resonant frequency of the charge carriers, $1/(2\pi\tau)$. With the presence of poorly conductive or dielectric materials in a sample, the vibration frequency of the KP (typically in the hundreds of Hz to single kHz range) may be higher than the resonant frequency of the space charge, and thus the measured electric potential is lower than the steady state's because the space charge is underdeveloped. This situation applies to, for example, painted surfaces of metals. The coating