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Space Charge Measurement Using Pulsed Electroacoustic Technique and Signal Recovery

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Abstract

A recurrent problem in high-voltage engineering is the measurement of the electric stress inside a solid dielectric subjected to high voltages. The electric stress distribution can be modified if space charge is present in the dielectric. The space charge can modify the local electric stress that may have an effect on the performance of the material. Therefore, the design, longevity, and performance of dielectrics, used as either electrets or insulators, depend on the space charge and the electric stress within them. Here a non-destructive experimental technique is considered which gives space charge and electric stress distributions inside dielectric samples by using acoustic pulses. However, it is realised that the technique does not give a true representation of the space charge when dispersive materials are considered. This paper presents a frequency domain algorithm giving an accurate space charge distribution enabling the method to be applied to either dispersive or non-dispersive dielectric materials. © 1999 Elsevier Science Limited. All rights reserved

Keywords: space charge, dielectric properties, electrical properties, piezolectric properties, ferroelectric properties.

1 Introduction

The most important advance in the study of the space charge has been the development of techniques to measure space charge non-destructively in dielectric materials (electrets[1] or insulator[2]) when they are subjected to an electric stress. These modern techniques apply ultrasonic waves to obtain the charge profile of a dielectric sample and can be divided into two groups in terms of how the acoustic wave is generated: the pressure wave propagation (PWP) method[3,4] where the acoustic waves are induced externally either by piezoelectric or by laser, and the pulsed electroacoustic (PEA)[5–7] method, where the acoustic waves are induced internally by charges exiting in the sample under an applied pulse voltage. A description of the PWP and PEA techniques has been published elsewhere.[5–7] However, a detailed description of the application of the two methods to a dispersive material has not been fully achieved.

In the present paper after a brief description of the principle of the PEA method, a signal processing technique is proposed to recover the real charge distribution within dispersive samples by taking the attenuation and dispersion factors of the material into account. The effectiveness of the technique has been demonstrated on low-density polyethylene (LDPE) samples.

2 Pulsed Electroacoustic Method

Figure 1 shows the principle of the PEA method. Consider a disc sample with thickness d and suppose that there is space charge $\rho(z)$ trapped in the sample. In order to measure the space charge we apply a high-voltage narrow pulse $e_p(t)$ of duration ΔT with a short rise and fall time to the sample between its electrodes 1 and 2. The application of this pulse produces electric stress (Lorentz force), creating pulsed acoustic pressure waves in each charge layer. By detecting the resultant pressure $p(t)$ arriving at the piezoelectric transducer in intimate contact with the electrode 1, we can obtain the charge distribution in the dielectric sample from the output voltage $v, (t)$ of the transducer. A mathematical description of the PEA method can be found in published work.[5–7]

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3 Acquisition of the Signal and Deconvolution

If the bandwidth of the transducer is less than that of the voltage pulse used to measure the space charge, the output voltage signal shape from the piezoelectric transducer will be different from the pressure waveform shape applied. The transducer together with the input impedance of the amplifier 50Ω, is a typical high-pass filter which attenuates low frequency components of the signal. As a result, the signal is often distorted as seen in Fig. 2.

Accordingly, the spatial charge distribution cannot be obtained directly from this voltage signal. Therefore, a signal processing must be applied to the output voltage signal which removes the frequency response of the piezoelectric transducer. This technique is called deconvolution.[6,7] Fig. 3 shows the signal after applying the deconvolution technique.

4 Attenuation and Dispersion of the Acoustic Wave

The spectrum of a transmitted pulse in a dispersive medium can be express as:[8]

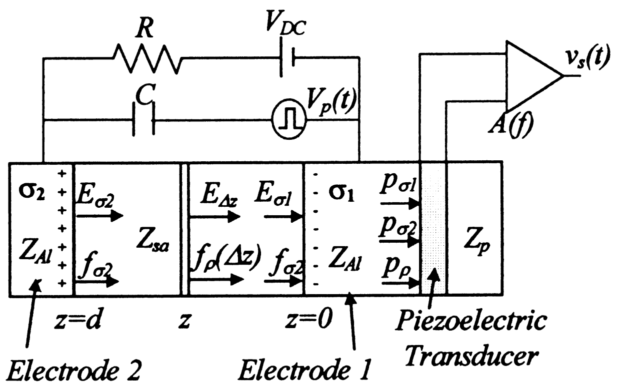

Fig. 1. Principle of pulsed electroacoustic method.

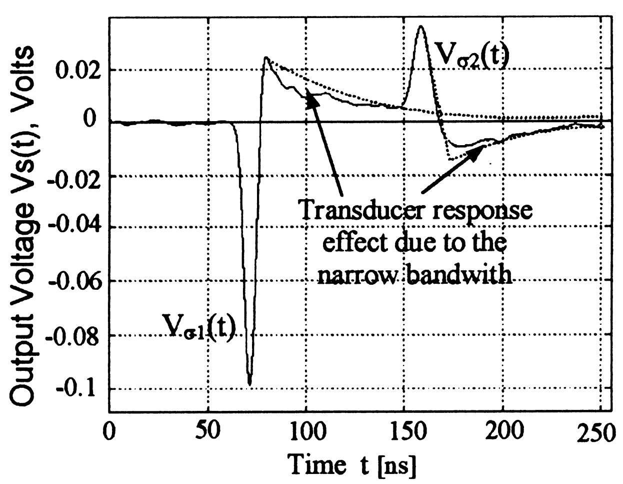

Fig. 2. Experimental result from a sample of LPDE (d=200 μm) when a DC electric voltage, $V_{DC}=-3$ kV is applied. The Vp pulse was of 5 ns and $V_p=400$ V.

$$P(f, z) = P(f, 0)\cdot\exp(-\alpha\cdot z)\cdot\exp(-j\cdot\beta\cdot z) \quad (1)$$

where $P(f, 0)$ is the Fourier transform of the input pulse at $z = 0$.

The attenuation and dispersion factors of the sample can be calculated by considering eqn (1) at two known points, for instance, $z = 0$ and $z = d$ as shown in the following equations:

$$\alpha(f) = -\frac{1}{d}\cdot\ln\left|\frac{P(f, d)}{P(f, 0)}\right| \quad (2)$$

$$\beta(f) = \frac{1}{d}\cdot[\phi(f, d) - \phi(f, 0)] \quad (3)$$

where $|P, (f, 0)|$ and $|P(f, d)|$ are the amplitude spectrum for the wave at $z = 0$ and $z = d$, respectively. $\phi(f, 0)$ and $\phi(f, d)$ are the phase spectrum of the original acoustic wave at $z = 0$ and the transmitted acoustic pulse at $z = d$, respectively.

In order to experimentally obtain $\alpha(f)$ and $\beta(f)$, it is only necessary to know the frequency spectra of the input wave pressure $P(f, 0)$, that correspond to $P_\sigma(f)$ and the output wave pressure $P(f, d)$, corresponding to $P_{\sigma 2}(f)$ and substitute them into eqns (2) and (3). A fast-Fourier transform algorithm was used to compute the amplitudes and phase of the first and second peak in the frequency domain. Figure 4 shows a typical graph of the attenuation and dispersion factors.

5 Signal Recovery

The numerical method for the accurate space charge profile has been performed in the time

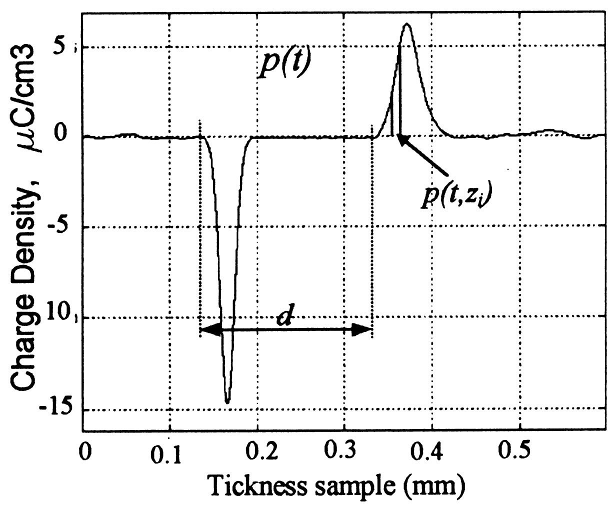

Fig. 3. Charge density distribution after deconvolution. The data corresponds to the signal shown in Fig. 2. It can be noted that there is only surface charge due to the low electric stress applied. This allows the value of the charge at $z = 0$ and $z = d$ to be found and to evaluate the attenuation and dispersion factor of the sample.

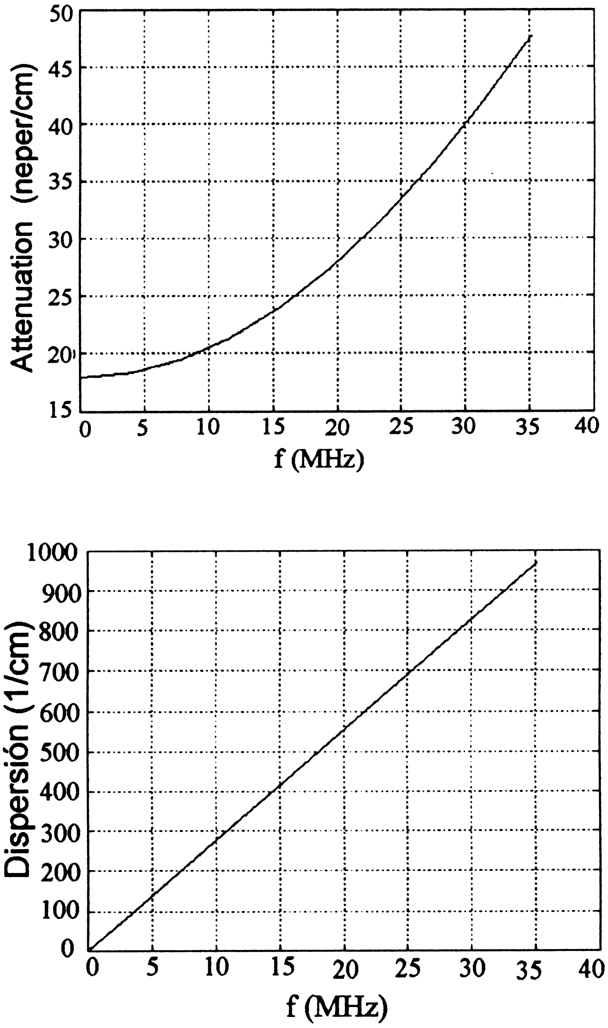

Fig. 4. Attenuation and dispersion versus frequency obtained in a sample of LPDE.

domain.[9] In this paper the Fourier transform to recover the space charge in the frequency domain (N is the number of sampled points) has been used.

In the time domain, the acoustic wave after deconvolution (Fig. 3) can be represented by the following,

$$p(t) = p(t, z_I) + \ldots + p(t, z_N) = \sum_{i=1}^{N} p(t, z_i) \quad (4)$$

The FFT (fast-Fourier transform) of the signal will be

$$P(f) = P(f, z_1) + \ldots + P(f, z_N) = \sum_{i=1}^{N} P(f, z_i) \quad (5)$$

$P(f, z_i)$ is the FFT of one layer at the position z_i of the time domain signal. Thus, the sum of each FFT of every layer in the time domain is the global FFT of the total time domain wave:

$$P(f) = \sum_{i=1}^{N} P(f, z_i) = FFT\left(\sum_{i=1}^{N} p(t, z_i)\right) \quad (6)$$

To recover the signal the effect of attenuation and dispersion must be considered layer by layer as shown in the following equation. For the layer z_i

$$P(f, z_i)_r = P(f, z_i)\cdot\exp(+\alpha\cdot z_i)\cdot\exp(+j\cdot\beta\cdot z_i) \quad (7)$$

where z_i indicates the charge layer at position z_i, and the subscript r indicates the signal recovered.

Based on the principle of superposition and using eqns (6) and (7), the complete signal recovery can be written as:

$$P(f)_r = \sum_{i=1}^{N} [P(f, z_i)\cdot\exp\{(+\alpha(f) + j\cdot\beta(f))\cdot z_i\}] \quad (8)$$

The relationship between initial pulse $P(f, 0)$ with the transmitted pulse $P(f, z)$ eqn (1) permits the definition of the transfer function of the sample at the position z_i as:

$$[A(f)]^{zi} = \frac{P(f, z)}{P(f, 0)} = [e^{\{-[\alpha(f)+j\cdot\beta(f)]\}}]^{z_i} \quad (9)$$

Equation (9) reduces the operations compared to use $\alpha(f)$ and $\beta(f)$. We can obtain directly $A(f)$ by applying eqn (9) to $z = d$:

$$A(f) = \left(\frac{P(f, d)}{P(f, 0)}\right)^{\frac{1}{d}} \quad (10)$$

Taking eqns (10) into (8), the signal recovery can be obtained by means of

$$P(f)_r = \sum_{i=1}^{N} P(f, z_i)\cdot A(f)^{-z_i} \quad (11)$$

6 Algorithm for Signal Recovery

The following steps are necessary:

1. Charge profile array before conversion to the time domain (N is the number of sampled points),

$$p(t) = [p(t, z_1), p(t, z_2), \ldots, p(t, z_N)] \quad (12)$$

2. Charge profile array before conversion in the frequency domain (FFT):

$$P(f) = FFT\{[p(t, z_1), p(t, z_2), \ldots, p(t, z_N)]\} = \\ = [P(f, z_1), P(f, z_2), \ldots, P(f, z_N)] \quad (13)$$

3. Recover signal layer by layer at frequency domain:

$$P(f, z_i)_r = P(f, z_i)\cdot A(f)^{z_i} \quad (14)$$

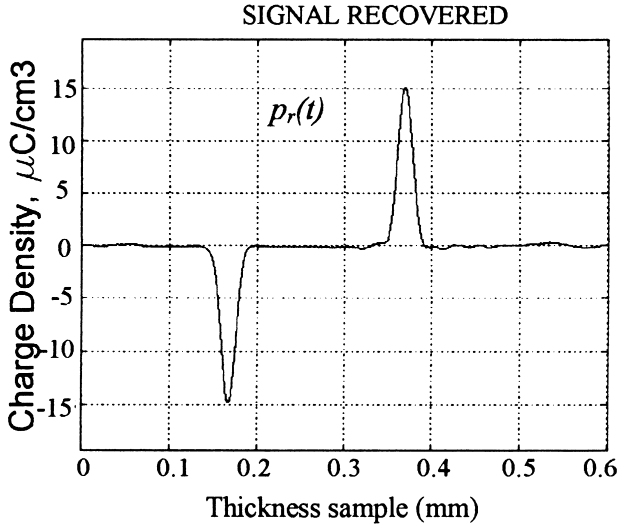

Fig. 5. Charge profile after recovering.

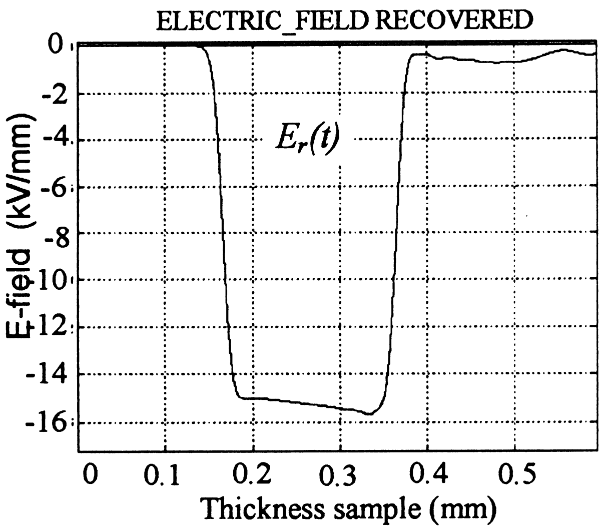

Fig. 6. Electric field calculated from real charge profile.

4. Apply superposition to obtain the total spectrum at frequency domain:

$$P(f) = \sum_{i=1}^{N} [P(f, z_i) \cdot A(f)^{z_i}] \tag{15}$$

5. Obtain the spectrum at time domain (IFFT):

$$p(t) = IFFT\left(\sum_{i=1}^{N} [P(f, z_i) \cdot A(f)^{z_i}]\right) \tag{16}$$

Figure 5 shows the modified charge profile. In this instance, the applied electric stress is too low a value and is not of long enough duration to produce bulk charge. Only an equal amount of surface charge on the electrodes is expected.

Following the analysis the electric stress distribution inside the sample can be found as shown in Fig. 6.

7 Conclusions

The principle of the PEA technique has been described and a frequency domain algorithm to recover the real space charge distribution is presented. Recovery is achieved by taking the attenuation and dispersion factors of the material into account. This enables the technique to be used for either non-dispersive or dispersive dielectric materials. The effectiveness of the PEA technique has been demonstrated on low-density polyethylene (LDPE) sample. Based on the correct charge distribution, the electric stress across the sample can be calculated.

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