Research Article

Iterative Deconvolution of PEA Measurements for Enhancing the Spatial Resolution of Charge Profile in Space Polymers

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This work aims to improve the PEA calibration technique through defining a well-conditioned transfer matrix. To this end, a numerical electroacoustic model that allows determining the output voltage of the piezoelectric sensor and the acoustic pressure is developed with the software COMSOL®. The proposed method recovers the charge distribution within the sample using an iterative deconvolution method that uses the transfer matrix obtained with the new calibration technique. The obtained results on theoretical and experimental signals show an improvement in the spatial resolution compared with the standard method usually used.

1. Introduction

In space applications, dielectrics placed on satellites can become electrically charged under the effect of bombardment with charged particles or ionizing radiation. This dielectric charging can reach a level of voltage capable of initiating a fast discharging process referred to as electrostatic surface discharge, which causes harmful interference with electronic components [1, 2]. To better control the discharging process, it becomes imperative to determine the kind, distribution, and amount of bulk charges with time and to understand the charge carrier in dielectrics used in satellites. The pulsed electroacoustic method (PEA) has been used to this end [3–9]. This technique, however, is known to be limited to about 10 μm in spatial resolution. Given the fact that the dielectric thickness used in spacecraft structure can be about 50 μm , such a resolution is not adequate. Therefore, enhancing PEA resolution is necessary to ensure accurate information about charge carrier.

In [10], the charge distribution in dielectric material was estimated using a reference signal determined from a DC

constraint on a blank sample. The reference signal serves to determine the transfer function of the piezoelectric sensor. This method, however, results in an ill-conditioned transfer matrix that negatively affects the resolution of charge distribution. In [11], a full PEA model was developed with the aim of optimizing the cell design. The model is capable of predicting the voltage signal of the piezoelectric sensor for any charge profile in the sample. Based on this full model, this paper proposes a new iterative deconvolution method that results in a well-conditioned transfer matrix of the entire cell. The proposed method is tested on simulated and experimental signals. Results show a good correlation between the simulated and the real charges. In addition an improvement in resolution is achieved compared with the conventional method.

The rest of the paper is organized as follows: Section 2 briefly recalls the PEA measurement principle and presents an electroacoustic model for the PEA cell, Section 3 recalls the calibration method of [10] and details the proposed calibration method, Section 4 studies the performance of the

FIGURE 1: PEA measurement principle.

FIGURE 2: The COMSOL model of PEA cell [11].

two methods on simulated and experimental data, and finally Section 5 provides the summary and conclusion.

2. Pulsed Electroacoustic Cell

2.1. PEA Measurement Principle. Figure 1 shows the PEA measurement principle. An insulator is inserted between the two electrodes E1 and E2 and an SC-film is placed between E2 and the sample to ensure better acoustic impedance. An electric impulse $e(t)$ on E1 is applied to excite charges within the sample.

As a result of this excitation, an acoustic wave $p(t)$ is produced in the sample and propagates through E2. The acoustic transducer converts this wave into an electric signal $V_s(t)$. This signal is amplified by a 30 dB amplifier and then processed to explore the charge profile.

2.2. Electroacoustic Model. Acoustic wave propagation is simulated using COMSOL® [12]. The numerical model of the PEA cell is divided into five domains: E1, sample, E2, PVDF, and the absorber (Figure 2). This model is able to simulate the acoustic wave propagation for any charge distribution.

Figure 3 shows a charge density profile and its corresponding output voltage signal, usually referred to as the calibration signal, when a noncharged sample is considered. This simulated voltage signal will be used to analyze and compare the charge profile estimated using the calibration method proposed by Maeno et al. in [10], denoted as Method 1, with the charge profile estimated by the iterative deconvolution method proposed in this work, denoted as Method 2.

3. Signal Processing

3.1. Aim of PEA Signal Processing. PEA signal processing is one of the important steps for estimating space charge in sample. The purpose of PEA system is to determine charge profile $\rho_{\text{calibration}}$ given in (1), knowing the output voltage $V_s(t)$ and adjusting the PEA transfer function H_{PEA} :

$$V_s = H_{\text{PEA}} \cdot \rho_{\text{calibration}} \quad (1)$$

Determining H_{PEA} passes through an initial procedure known as calibration. In the following, we explain this approach for Method 1 and Method 2.

FIGURE 3: (a) The net charge density for a charged sample using normalized value. (b) Sensor output voltage.

FIGURE 4: Flow chart of the signal processing based on Method 1.

3.2. Signal Processing Used by Method 1. The signal processing used by Method 1 relies on the convolution product between charge profile and the electric pulse. In the frequency domain, we have

$$P(f) = K \cdot v_{\text{sample}} \cdot R(f) \cdot E(f) \cdot \exp\left(-i2\pi f \cdot \frac{l}{v_{Al}}\right), \quad (2)$$

where K is a constant, v_{sample} and v_{Al} are, respectively, the sound velocities in the sample and E2, and l is the thickness of electrode E2. $R(f)$, $E(f)$, and $P(f)$ are, respectively, the Fourier transform of charge density $\rho(t)$, electric pulse $e(t)$, and pressure wave $p(t)$. As shown in Figure 2, the transfer function of the piezoelectric transducer is the only unknown:

$$V_s(f) = H_{\text{sensor}}(f) P(f). \quad (3)$$

This function (H_{sensor}) is determined assuming a Dirac distribution of electric charge at E1 and E2. Then, $R(f) = 1$ and (2) becomes

$$P_{\text{calibration}}(f) = A \cdot E(f) \cdot \exp\left(-i2\pi f \cdot \frac{l}{v_{Al}}\right), \quad (4)$$

$$V_{\text{calibration}} = P_{\text{calibration}} \cdot H_{\text{sensor}},$$

where A is a constant determined from the total electric charge Q in sample. Using (1)–(4), the charge profile could be calculated as follows:

$$R(f) = \frac{A \cdot V_s(f)}{K \cdot v_{\text{sample}} \cdot V_{\text{calibration}}(f)}. \quad (5)$$

H_{PEA} can be expressed theoretically as

$$H_{\text{PEA}} = \frac{K \cdot v_{\text{sample}} \cdot V_{\text{calibration}}(f)}{A}. \quad (6)$$

FIGURE 5: Estimated charge profile by Method 1.

Obtaining the charge distribution $\rho(x)$ experimentally requires dividing $V_s(f)$ by $V_{\text{calibration}}(f)$ and determining the inverse Fourier transform of $R(f)$. As shown in Figure 4, this is achieved by a deconvolution technique that uses two functions: a Gauss function to limit the frequency range of the signal spectrum filter and a Wiener function to avoid the division by zero in the Fourier domain [13, 14]. The inconvenience of using Gauss filter has to manually set a parameter R that is directly linked to the bandwidth. A low bandwidth provides high value of R , whereas a low value of this parameter involves a higher cut-off frequency (the effect of R is discussed later).

Accounting for the practical considerations of this implementation, the expression of H_{PEA} is then written as

$$H_{\text{PEA}} = \frac{K \cdot \nu_{\text{sample}} \cdot V_{\text{calibration}}(f) \cdot H_{\text{Wiener}}(f)}{A \cdot H_{\text{Gauss}}(f)}. \quad (7)$$

Finally, the charge profile of the sample can be determined after defining the Wiener function, the Gauss filter whose parameter R is set manually, and the constant A which is related to the surface charge Q . Figure 5 shows the normalized estimated charge profile on one electrode calculated by Method 1, which consists of Gaussian-shaped pulse instead of the Dirac pulse of the true profile. Therefore Method 1 did not respect the initial assumption.

3.3. Calibration Method and Signal Processing of Method 2. In [11], it was found that using Dirac distribution that leads to determine the PEA transfer matrix did not guarantee a well-conditioned system that affords the same shape and amplitude of electric charge in a sample. To enhance the condition number of the PEA transfer matrix, we propose to adopt the Gaussian distribution for the electric charge. Hence, the electric charge density on both electrodes is assimilated to a Gaussian shape centred on the corresponding electrode, as depicted in Figure 6. The charge distribution is then given by

$$\rho_{\text{calibration}} = A_{\text{cal}} \cdot e^{-2(x-x_0)^2/d^2}, \quad (8)$$

where x_0 is the position of electric charge and A_{cal} and d are the amplitude and spreading of the electric charge profile, respectively.

FIGURE 6: Electric charge profile used in calibration method.

In addition, the net electric charge density Q on both electrodes is considered to be equal to the capacitive charge $Q = C_s U$, where C_s is the sample surface capacitance and U is the applied voltage. A_{cal} is related to the electric charge Q and to the charge spreading d by the following relation:

$$Q = C_s U = \int_{-\infty}^{+\infty} A_{\text{cal}} e^{-2(x-x_0)^2/d^2} dx = \frac{A_{\text{cal}} d}{\sqrt{\pi/2}}. \quad (9)$$

It can be seen that once d is known, $\rho_{\text{calibration}}$ can be determined.

3.4. Characterization of the PEA Transfer Matrix Based on the Gaussian Distribution-Method 2. Calibration is an essential stage for an accurate determination of the electric charge distribution using PEA method [10, 15, 16]. The goal of the new calibration method is to determine the PEA transfer matrix. The proposed method starts by relating $V_{\text{calibration}}$ which is the response of the capacitive charge $\rho_{\text{calibration}}$ on the electrodes, to $\rho_{\text{calibration}}$ by Toeplitz matrix H_{PEA} constructed from the impulse response $H_{\text{PEA}}(t)$ of the PEA cell [17]:

$$V_{\text{calibration}} = H_{\text{PEA}} \rho_{\text{calibration}} \quad (10)$$

with

$$H_{\text{PEA}} = \begin{bmatrix} h_1 & 0 & \cdots & \cdots & 0 & h_{n_h} & \cdots & h_2 \\ h_2 & h_1 & 0 & \cdots & \cdots & 0 & h_{n_h} & \cdots \\ \vdots & h_2 & h_1 & 0 & \cdots & \cdots & 0 & h_{n_h} \\ h_{n_h} & \vdots & h_2 & h_1 & 0 & \cdots & \cdots & 0 \\ 0 & h_{n_h} & \vdots & h_2 & h_1 & 0 & \cdots & \cdots \\ \vdots & 0 & h_{n_h} & \vdots & h_2 & h_1 & 0 & \cdots \\ \vdots & \vdots & 0 & h_{n_h} & \vdots & h_2 & h_1 & 0 \\ 0 & \vdots & \vdots & 0 & h_{n_h} & \vdots & h_2 & h_1 \end{bmatrix}, \quad (11)$$

$$\rho_{\text{calibration}} = \begin{pmatrix} \rho_0 \\ \rho_1 \\ \vdots \\ \rho_{n_c-1} \\ \rho_{n_c} \\ 0 \\ \vdots \\ 0 \end{pmatrix},$$

$$V_{\text{calibration}} = \begin{pmatrix} v_0 \\ v_1 \\ \vdots \\ v_{N-1} \\ v_N \end{pmatrix},$$

where n_h , n_c , and $N = n_h + n_c - 1$ are the numbers of samples of $H_{\text{PEA}}(t)$, $\rho_{\text{calibration}}$, and $V_{\text{calibration}}$, respectively.

Equation (10) can be rewritten as

$$V_{\text{calibration}} = H_{\rho} \cdot H_{\text{PEA}} \quad (12)$$

with

$$H_{\text{PEA}} = \begin{pmatrix} h_1 \\ h_2 \\ \vdots \\ h_{n_h} \\ 0 \\ \vdots \\ \vdots \\ 0 \end{pmatrix},$$

$$H_{\rho} = \begin{bmatrix} \rho_1 & 0 & \cdots & \cdots & 0 & \rho_{n_c} & \cdots & \rho_2 \\ \rho_2 & \rho_1 & 0 & \cdots & \cdots & 0 & \rho_{n_c} & \cdots \\ \vdots & \rho_2 & \rho_1 & 0 & \cdots & \cdots & 0 & \rho_{n_c} \\ \rho_{n_c} & \vdots & \rho_2 & \rho_1 & 0 & \cdots & \cdots & 0 \\ 0 & \rho_{n_c} & \vdots & \rho_2 & \rho_1 & 0 & \cdots & \cdots \\ \vdots & 0 & \rho_{n_c} & \vdots & \rho_2 & \rho_1 & 0 & \cdots \\ \vdots & \vdots & 0 & \rho_{n_c} & \vdots & \rho_2 & \rho_1 & 0 \\ 0 & \vdots & \vdots & 0 & \rho_{n_c} & \vdots & \rho_2 & \rho_1 \end{bmatrix}. \quad (13)$$

As shown in (12), H_{ρ} is a Toeplitz matrix constructed from the samples of the charge distribution used in calibration. Knowing $V_{\text{calibration}}$, the impulse response of the system H_{PEA} can be determined (Figure 7).

In fact, a procedure of four steps is followed to determine the transfer matrix.

S1. Initialize the Gaussian shape at the Electrode/Sample interface by assigning to d the value of the thickness of the sensor (in order to accommodate the entire incoming signal) and then we deduce A_{cal} using (9).

S2. Construct a Toeplitz H_{ρ} matrix from electric capacitive charge $\rho_{\text{calibration}}$ according to (13).

S3. Determine the system impulse response. Once H_{ρ} is obtained and considering calibration signal $V_{\text{calibration}}$, the cell impulse response H_{PEA} is calculated as follows:

$$H_{\text{PEA}} = H_{\rho}^{-1} \cdot V_{\text{calibration}}. \quad (14)$$

S4. Assess the PEA transfer matrix through

$$\rho = H_{\text{PEA}}^{-1} \cdot V_s. \quad (15)$$

An enhanced result is achieved by using the following iterative procedure.

S1. Initialize a spreading d_h equal to the sensor thickness.

S2. Calculate the transfer matrix H_{PEA} .

S3. Deconvolve the reference signal to obtain $\rho_{\text{calibration}}$.

S4. Determine the calibration spreading d_c at the electrodes.

S5. Repeat step 1 with $d_h = d_c$ until $d_h - d_c = 0$.

This approach is illustrated in the flowchart shown in Figure 8. Using Method 2, the charge profile is obtained after the adjustment of only one parameter, which is the surface charge Q [18].

FIGURE 7: Estimation of H_{PEA} .

The utility of this method in obtaining accurate shape and amplitude of the normalized imposed charge profile on one electrode can be seen in Figure 9.

Unlike Method 1, Method 2 allows recovering the initial assumption.

4. Results

4.1. Simulated Data. This part is based on a comparison between Method 1 and Method 2 with respect to the spatial resolution of the charge profile. To do that, a charge distribution in a $300\ \mu\text{m}$ sample is considered as input for the electroacoustic model. As shown in Figure 10, this charge distribution possesses two negative peaks distant by $5\ \mu\text{m}$ in the middle of the sample along with image charges at the electrodes. Feeding this distribution to the model yields the output voltage $V_s(t)$ also shown in Figure 10.

Based on the output signal and after finalizing the calibration steps, charge distributions are determined using Method 1 and Method 2. They are given in Figures 11 and 12,

respectively. Method 1 requires defining the parameter R . Two different values of R were tested: $R = 5$ and $R = 8$. For $R = 5$ the shape of the charge distribution is completely different from the original shape due the presence of oscillations. The reason is that the cut-off frequency is not adequate to remove all the noise. For $R = 8$, the noise is almost completely suppressed. However, a part of useful signal is eliminated due to the value of the cut-off frequency of the low pass-filter. Indeed, in this case, the two peaks cannot be discerned. This example clarifies the trade-off between high signal quality and resolution.

Figure 12 shows estimated charge using Method 2. It can be seen that the charge estimated is very close to the original shape. Some disturbances appear around each peak. This effect is due to the high condition number of the overall transfer function which is higher than 1.

4.2. Experimental Data. This study is carried out for two different samples: a PTFE sample of $300\ \mu\text{m}$ thickness and

FIGURE 8: Flowchart of the signal processing implementation of Method 2.

FIGURE 9: Estimated charge profile by Method 2.

an FEP sample of $250\ \mu\text{m}$ thickness. It consists of calibration followed by estimation of charge profile after irradiation.

4.3. Calibration. The calibrated profile is obtained from a PEA measurement of a polarized blank PTFE sample. Polarization is done after 10 s under 3 kV. Figure 13 shows the acquisition system and the PEA cell device. The PEA cell is placed in an enclosure to eliminate interference induced by the local environment.

Figure 14 shows the charge density estimated by Method 1 and Method 2 during calibration. The value of parameter R is set to 10 since this value eliminates oscillations and provides a proper signal. In this step of measurement, we can notice a difference between the two charges profiles.

From Figure 14(a), it can be seen that Method 1 results in a resolution of $9\ \mu\text{m}$ and a maximum value of $18\ \text{C}\cdot\text{m}^{-3}$, whereas Method 2 results have a spatial resolution of $6\ \mu\text{m}$ with a maximum value of $24\ \text{C}\cdot\text{m}^{-3}$. Moreover, the Bode

FIGURE 10: Simulated charge density and output voltage.

FIGURE 11: Estimated charge distribution by Method 1.

FIGURE 12: Estimated charge distribution by Method 2.

FIGURE 13: Acquisition system (to the left) and PEA cell device (to the right).

diagram of the output PEA signal in Figure 14(b) shows that the bandwidth is largest when Method 2 is used, thus affording a better resolution of the charge distribution within the sample. Indeed, the bandwidth defined at -3 dB is about 19 MHz for Method 1 and 69 MHz for Method 2.

4.4. Estimation of the Charge Profile after Irradiation. A PTFE sample was irradiated at 30 keV during 20 minutes using SEM. Figure 15 presents a comparison of charge profiles after irradiation obtained using Method 1 and Method 2. An

improvement of the spatial resolution is observed, as the full width at half maximum is $6 \mu\text{m}$ for Method 2 versus $9 \mu\text{m}$ for Method 1. Another remark from Figure 15 is that a lower penetration of charge in the bulk occurs when Method 2 is used; a maximum value of $6.8 \mu\text{m}$ compared with $9.1 \mu\text{m}$ for Method 1.

FIGURE 14: (a) Calibrated charge distribution. (b) Bode diagram calculated by Method 1 and Method 2 for PTFE.

FIGURE 15: Charge profile calculated by Method 1 and Method 2 for PTFE after irradiation.

These methods were also tested on a $250 \mu\text{m}$ thick FEP sample. The dedicated irradiation chamber SIRENE [19–21] and a special PEA cell without contact Figure 16 were used in order to determine the charge profile. The same flux of electrons, of about $100 \text{ pA}\cdot\text{cm}^{-2}$, was used for two energy levels at 20 keV and 145 keV.

The result of Method 1 was obtained for $R = 10$, whereas those of Method 2 were calculated automatically. The 20 keV aims to implement electrons close to the irradiated surface. For the 145 keV, however, charges are injected approximately

FIGURE 16: Schematic of PEA without contact cell device adopted in SIRENE.

at the middle of the samples. This phenomenon was observed for both methods, but the advantage of Method 2 resides in the automatic calculation of the charge profile within the samples. Moreover, an enhancement of charge resolution has been obtained (Figure 17(a)), mainly at the electrode-sample interface. In addition, the difference in percentage between the amplitude of charges density issued from the 20 keV between Method 2 and Method 1 is about 13%. However, for the 145 keV, this difference is 50%.

Figure 17(b) shows the profile of charge density issued from the 145 keV. The full width at half maximum (FWHM) and the total electric charges can be estimated. Method 1 gives a resolution of $\text{FWHM} = 10.6 \mu\text{m}$ and a maximum charge

FIGURE 17: Charges profiles issued from FEP sample after irradiation using Method 1 and Method 2. (a) With an energy of 20 keV. (b) With an energy of 145 keV.

of $68 \text{ C}\cdot\text{m}^{-3}$, while with Method 2 the spatial resolution is $\text{FWHM} = 9.4 \mu\text{m}$ and with a maximum charge of $92 \text{ C}\cdot\text{m}^{-3}$.

5. Conclusion

This paper presented a new calibration method based on an iterative deconvolution scheme that aims to determine the PEA transfer function. The iterative nature of the proposed method allows overcoming the ill conditioning of the transfer matrix and thus improving the quantitative interpretation of the results. For both simulated and experimental data, results obtained by the proposed method showed improvement in the spatial resolution of the charge density profile and oscillation suppression, when compared with those of a method used in the literature. Also, in contrast to the calibration methods usually used where a resolution parameter must be defined without any physical criterion (only visual quality of the result allows defining this parameter), the proposed method yields a well-conditioned transfer matrix without human intervention.

Competing Interests

The authors declare that they have no competing interests.

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