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Measuring technique for static electricity using focused sound

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ABSTRACT

A novel method is proposed for non-contact measurement of the distribution of electrostatic charge on a surface based on scanning the sample surface with a focused high frequency acoustic beam to excite movement of the sample surface. An electric field is induced by exciting a charged film-like object, and an electric field sensor measures it instead of an electrostatic field. The focused ultrasound waves are generated by controlling individually the phase of each 285 airborne ultrasound transducers.

1. Introduction

Static electricity measurements are important in managing efficiency in the production of electronic devices that are sensitive to static charges. Measurement technologies developed thus far, including field mill type [1–3], static induction type [4], vibrating reed induction type fieldmeters [5], chopper stabilized instruments [6], Pockels effect sensors [7,8], Kerr effect sensors [9,10], and scanning probe microscopes [11,12], use targeted electrostatic fields. However, as such sensors cannot distinguish spatially separated charges within a measurement region, when they are used to measure static electricity distributions within an object plane, it is necessary to narrow the measurement region by narrowing the input into the sensor and scanning point-by-point [13]. As a result, measurements of static electricity distributions are quite costly in terms of time.

Plastic film, which is flexible, easy to work with, and an excellent electrical insulator, is used as a substrate for next-generation devices such as flexible and printed electronics. As these devices are sensitive to static electricity and their thin plastic film substrates are easily charged in the production process, measurement of charge buildup is therefore important. Furthermore, they tend to develop inhomogeneous charge distributions. As a result of these factors, it is necessary to develop techniques capable of quickly measuring static planar electricity distributions.

We propose a technique for measuring static electricity by using sound wave irradiation to vibrate a charged object, thus inducing an electric field [14]. The static electric field of the object can then be detected by measurement of this induced field. This method is based on previously developed technologies for measurement of static electricity by excitation of charged objects [14] and for noncontact excitation using focused ultrasound [15]; in this study, we discuss these two elements in technical detail.

2. Theory

2.1. Static electricity measurement by excitation of a charged object

The electric field E [V/m] resulting when charge q [C] oscillates along the *z*-axis can be derived from the theory of dipole radiation. Using polar coordinates, the equation of the generated electric field can be given as [15]

$$\begin{aligned}\mathbf{E} =& \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2}\mathbf{e}_r + \frac{1}{2\pi\varepsilon_0}\left\{\frac{ql}{r^3} + \frac{q\dot{l}}{c_0 r^2}\right\}\cos\theta\,\mathbf{e}_r \\ &+ \frac{1}{4\pi\varepsilon_0}\left\{\frac{ql}{r^3} + \frac{q\dot{l}}{c_0 r^2} + \frac{q\ddot{l}}{c_0^2 r}\right\}\sin\theta\,\mathbf{e}_\theta\end{aligned} \tag{1}$$

where ε_0 [F/m] is the permittivity of the vacuum, c_0 [m/s] is the speed of light in a vacuum, l [m] is the displacement of the charge, is a temporal differentiation of displacement, r [cm] is the distance of

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the observation point from the charge, θ [rad]is the angle between the z-axis and the x–y plane, and $\mathbf{e}_r$ and $\mathbf{e}_\theta$ are the unit vectors in the r- and θ-directions, respectively. The first term on the right-hand side of equation (1) represents an electrostatic field. As it is difficult to distinguish whether this term is generated by the object or the environment, it is excluded here as unsuitable for use in the detection of static electricity. The other terms describe time-varying electric fields. As an example, for an electric field generated by a charge with a displacement amplitude of 1 mm and frequency of oscillation of 100 Hz and measured at $\theta = 0$ rad, $r = 10$ cm, the dominant term is given by

$$\mathbf{E} = \frac{1}{2\pi\varepsilon_0}\frac{ql}{r^3}\mathbf{e}_r \tag{2}$$

By measuring the electric field **E**, the charge q can be determined. The dominant of E-component is approximately 50%.

2.2. Noncontact excitation by focused ultrasound

When an object acts as an obstacle for the transmission of an ultrasonic wave, stress is generated on the object's surface in the form of acoustic radiation pressure especially along the propagation direction of the wave [16,17]. By using this phenomenon, a target object can be excited remotely. A plane ultrasound wave normally incident to the surface of an object will generate an acoustic radiation pressure P [Pa] of

$$P = \alpha\frac{p^2}{\rho c^2} \tag{3}$$

where α is a coefficient based on the amount of reflection from the object's surface (in the case of total reflection, $\alpha = 2$), p [Pa] is the ultrasound pressure, ρ is the air density (1.2 kg/m^3), and c is the speed of sound (340 m/s).

Ultrasound waves can be focused on a single point in the air by using ultrasound transducers to properly control phase. As the acoustic radiation pressure of each transducer is very weak, a few hundred must be used to obtain a pressure-generated force F of the order of tens of mN. This method can also be used to change the position of the focal point by manipulation of the phase of the waves. Thus, a specific force can be generated remotely at any position in space. When a rectangular transducer array is used, the diameter w [m] of the focal point can be given using [15]

$$w = \frac{2\lambda R}{D} \tag{4}$$

where λ is the ultrasound wavelength (8.5 mm), R [m] is the focal length from the transducer array, and D [m] is length of a side of the array. The spatial resolution of the technique discussed here is limited by this focal size and material hardness.

3. Experiment

The experimental setup, consisting of equipment to generate focused ultrasound and measure the resulting electric fields, is shown in Fig. 1. A small ultrasound device [18] was adapted to generate focused ultrasound waves. 285 ultrasound transducers were arranged in a rectangular array with $D = 17$ cm to deliver focused ultrasound with frequency 40 kHz to the focal point by generating driving signals corresponding to the phase difference between the transducers. From equation (4), the diameter of the focal point was 13 mm at a focal length of 130 mm. The maximum generated force at the focal point was 16 mN.

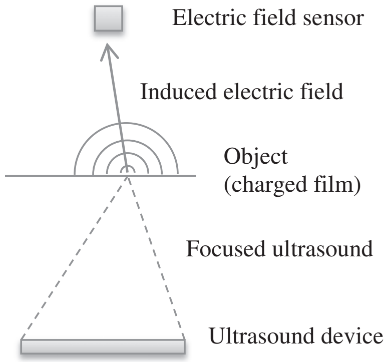

Fig. 1. Experimental setup of proposed measuring method. The system consists of equipment to generate focused ultrasound and to measure electric fields.

As seen in Fig. 1, the focused ultrasound device was placed at a 13-cm distance from the sample object. A jig to mount a line laser displacement meter (LJ-G200, Keyence Corp.) and an electric field detecting sensor were placed above the sample. Using a line laser displacement meter installed at 200-mm distance from the sample, z-axis charge displacement could be measured over a diameter of 62 mm on the x-axis at a sampling rate of 15 m. To detect electric fields, a lab-made, 150-mm long, nondirectional monopole antenna was connected to a preamplifier (60 dB gain) and a digital oscilloscope. The antenna was installed parallel to and 30 mm away from the sample plane. The samples, a 250 × 250 mm^2, 10-μm-thick vinyl chloride film and a 180 × 15 mm^2, 15-μm-thick aluminum film, were fixed between the measuring device and the focused ultrasound device using the jig.

4. Results and discussion

4.1. Displacement distributions on a sheet sample irradiated with focused ultrasound

An experiment was carried out to measure local charge displacements on an object's surface caused by irradiation of focused ultrasound. The ultrasound was used to irradiate the vinyl chloride sheet at a focal position that moved along the x-axis in intervals of 10 mm every 100 m. The resulting distributions of charge displacement were measured using the line laser displacement meter. Fig. 2 shows the series of one-dimensional distributions around the advancing center of the ultrasound focus. With each shift, the focal point moved a maximum of 1.5 mm, whereas the full widths at half maximum of the displacements were about 30 mm. Although the displacement ranges were wider than the 1.3-cm focal diameter of the beam, these results demonstrated that local excitation could be measured.

4.2. Measurement of an electric field induced by exciting charged sample

An experiment was carried out to measure the electric field induced when charged samples were excited using focused ultrasound. Five 180 × 15 mm^2, 15-μm-thick samples of aluminum film were arranged in parallel at intervals of 25 mm, as shown in Fig. 3. Voltages alternating between +500 V and −500 V were applied to these samples, and impulse excitations from focused ultrasound were delivered in sequence to the samples in intervals of 2 s. The electric fields induced by this process were measured using a monopole antenna positioned at a distance of 30 mm from the

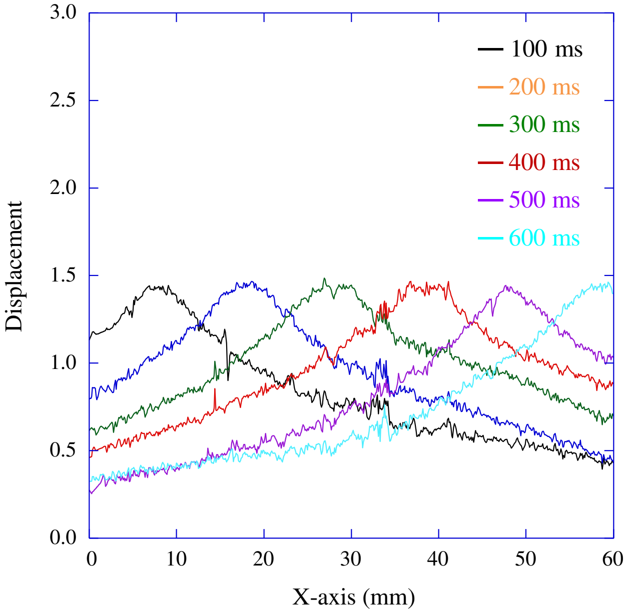

Fig. 2. One-dimensional distributions of displacement of vinyl chloride sheet along straight line through center of ultrasound focus.

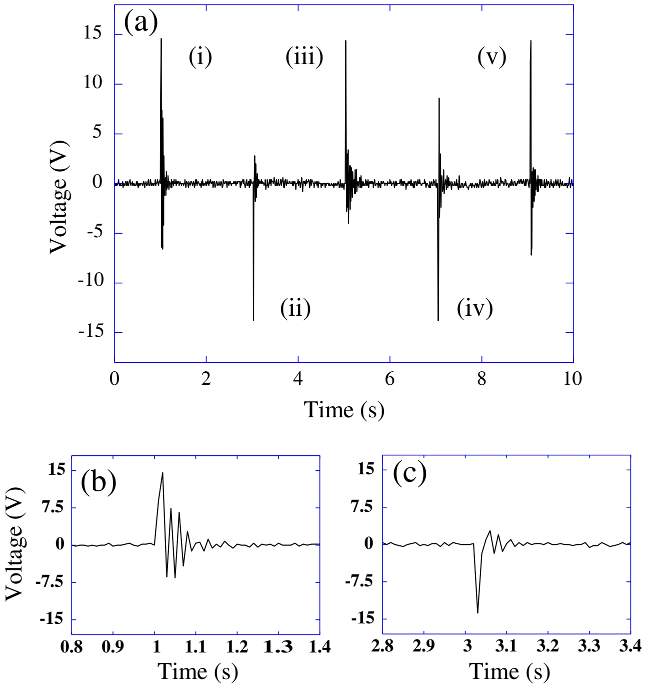

Fig. 4. Experimental results of measurement of electric field (a) measured fluctuation, (b) waveform of the first sample with +500 V applied, (c) waveform of the second sample with −500 V applied.

sample and oriented parallel to the direction of motion of the ultrasonic beam focus.

Fig. 4(a) shows the measured change over time of the electric field, representing impulse responses in the charged sample to the ultrasound excitation. It can be seen that the pulse variations in electric field occurred in 2-s intervals. Fig. 4(b), (c) shows expanded waveforms of the first and second impulse responses. Although the peak directionality is different for each waveform, the observed change in voltage is about the same in both. This result shows the successful detection of an electric field generated by a spatial change of charge, where the initial displacement direction of the waveform was dependent on the electrical polarity of the charges. If positive charges were excited, a positively phased electric field was detected; if negative charges were excited, the measured electric field had negative phase. Fig. 5 shows the results of measuring the change in electric field voltage following application of voltages in the range 0–500 V to the sample. It can be seen from this that the change in measured electric field is directly proportional to the voltage applied to the sample. These results show that static electricity can be evaluated quantitatively by measuring the change in

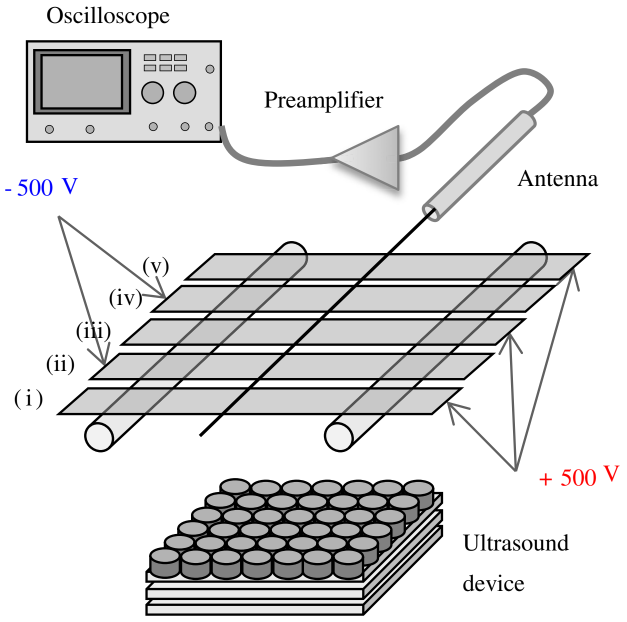

Fig. 3. Experimental setup for measurement of electric field induced by charge oscillation. Five samples are arranged in parallel at intervals of 25 mm, and an antenna is installed 30 mm from the sample and parallel to it.

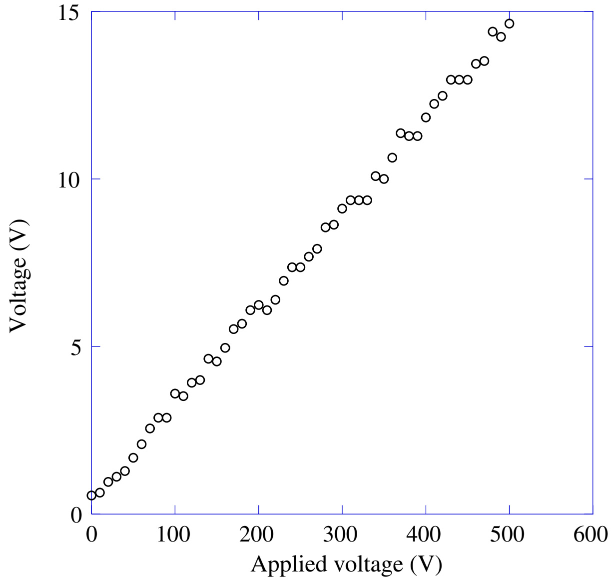

Fig. 5. Relationship between amount of change in electric field and applied voltage on film.

measured electric field. The error in measurement of static charge using this method is about 10%.

From Fig. 4, it can be also be seen that the signal voltage of the induced electric field returned to its equilibrium value within about 0.1 s of signal generation, indicating that the vibrated sample relaxed to its static state within the same time frame. Thus, static electricity within a 20-mm-diameter region can be measured within 0.1-s intervals using the focused ultrasound method. The time for excitation to self-dampen would be shortened by suppressing the vibration using anti-phase sound waves and tension control of the film. Furthermore, the distribution of static charge can be measured by simply scanning the focused ultrasound. The use of higher frequency would make it possible to measure with a finer resolution and a higher time resolution. In the case of 2D scan over the whole area of the sample, higher sensitivity could be achieved using a pick-up disc rather than a line pick-up wire antenna. For these reason, further high-speed measurement of static electricity distribution would be possible.

On the other hand, general practical application of the approach is limited for the following reasons: the spatial resolution would be affected the hardness of materials, the approach would not be suitable for materials that include fully conducting films such as semiconductor packaging films, quantitative measurements would require calibration in terms of the area density and flexibility, these could confuse observations in scanning because the acoustic excitation could create local resonances in the surface of the material. Therefore, if the measured value of the electric field is calibrated by measuring the local displacement of the point using a laser, measurement of static electricity using this approach would be possible to evaluate quantitatively.

5. Conclusions

In this study, a new method for measuring static electricity distribution using focused ultrasound was proposed and discussed. In this method, a time-varying electric field is generated by exciting a charged object and then using an antenna to determine the static electric charge distribution through measurement of the induced electric field and the phase of the resulting dipole electric field. Using focused ultrasound irradiation, excitation of surface charge on a sample target can be performed locally and without contact, with the focal position of the ultrasound beam controlled by tuning the phase differences between drive signals. Using this method, it is possible to measure static electricity distribution over an entire surface of an object by gradually adjusting the relative positions of an excitation device and a sensor.

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