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Development of a technique for measuring static electricity distribution using focused ultrasound waves and an induced electric field

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ABSTRACT

A novel method is proposed for non-contact measurement of static electricity distribution on a surface using focused ultrasound to excite movement of the charge. The focused ultrasound is generated by controlling individually the phases of 285 airborne ultrasound transducers, and it was demonstrated local excitation could be measured. An electric field is induced by local excitation of a charged object. The electric field intensity and phase are related to the surface potential and electrical polarity of the object, respectively. It is possible to measure static electricity distribution over an entire object surface by scanning the position of the focused ultrasound.

Introduction

In order to measure static electric charge on the surface of various materials, it is desirable to consider the charge distribution in terms of areas, rather than points. When electrostatic charge builds up on an insulating material, the charge is distributed unevenly over the surface. This is because electrical charges built up on the surface by localized frictions or detachments are not evenly distributed over the surface due to its insulating properties. Various types of surface potential sensors have been developed in the past as electrostatic meters for measuring charge at points, targeting the electrostatic field and electrostatic capacity [1–8]. It was necessary to bring such surface potential sensors to the proximity of a targeted sample objects and physically scan them in order to measure the electrostatic distribution accurately because readings from these sensors depend on their measurement ranges and the distance from the sensor to the target, and they are easily affected by electrostatic fields and grounding in the vicinity of the sensor [9]. A large amount of time was therefore required to take measurements of electrostatic distributions, which has been cited as a problem in terms of reproducibility in evaluating static electricity because such conditions change over time.

We intended to develop a technology for measuring static electricity that can be used to measure electrostatic distributions without moving the sensor and without applying stimulus to the electrostatically charged targets that will affect their electrostatic charge distributions so that changes in signals can be captured as readings. Acoustic waves were chosen as stimulus to be applied to the target to induce physical oscillations of the targets thus triggering electric charge oscillations and allowing quantitative evaluation of the static charge distribution by measuring the induced oscillations of the electric field [10]. Measurements of one-dimensional electrostatic charge distributions with the sensor fixed in place can be made by using pulsating excitation made possible by focused ultrasound [11]. In order to achieve our objective, however, we needed a two-dimensional scanning technology for localized oscillations and the ability to evaluate such two-dimensional oscillations in combination with corresponding low-frequency electric field measurements. In order to measure two-dimensional distributions of static electricity, the relationship between the acoustic pressure distribution of focused ultrasound using the phased array method and the localized surface oscillation had to be clarified in order to realize our scanning technology for inducing localized oscillations so that we could examine the method for detecting low-frequency electric field oscillations using plate electrodes.

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Experimental method

Electric field induction by electric charge oscillation

A conceptual diagram of electric field induction by electric charge oscillation for the purpose of electrostatic measurements is shown in Fig. 1. When an electrostatically charged sample object targeted for a measurement is physically oscillated, the electrostatic charge undergoes a spatial oscillation along with the sample object. This results in the spatial displacement of the electric charge with respect to time, and an electric field is induced in its surroundings. It is then possible to apply the theory of dipole radiation in order to derive the dominant term for the generated electric field using the equation below [12] for the cases where the electric field $\mathbf{E}$ [V/m] has a frequency of up to 1 kHz and an observation distance of up to 1 wavelength (300 km) when a charged particle with electric charge q [C] moves in the z direction:

$$\mathbf{E} = \frac{1}{4\pi\varepsilon_0}\frac{ql}{r^3}(2\cos\theta\mathbf{E}_r + \sin\theta\mathbf{E}_\theta)e^{-jkr}, \tag{1}$$

where l [m] is the displacement of the charged particle, r [m] is the distance from the charged particle to the observation point, k [m^{-1}] is the wavenumber, j is the imaginary unit, θ [rad] is the inclination from the z axis, while $\mathbf{e}_r$ and $\mathbf{e}_\theta$ are unit vectors in the r and θ directions, respectively. The electric charge can be derived by measuring this electric field. The surface potential, which is proportional to the electric charge, was used in our research to represent the magnitude of the static charge.

Focused ultrasound by phased arrays

Acoustic radiation pressure was used in our research to trigger localized oscillation of our sample objects in air and without being in close proximity [13–15]. Furthermore, ultrasound generated by using the phased array method can be focused to a single focal point in air by appropriately controlling the phases of the respective oscillators that are arranged in a plane. This method allows for moving the focal point by manipulating the phase making it possible to generate an oscillating force at an arbitrary position in space from a remote location. As shown in Fig. 2, when a rectangular oscillator array is used with a focal length of R [m], and the length of a side of the square array is D [m], the diameter of focal point w [m] is given by [16]:

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

where λ [m] is the wavelength of the ultrasonic wave. A trade-off relationship between the array size and spatial resolution is evident from Eq. (2).

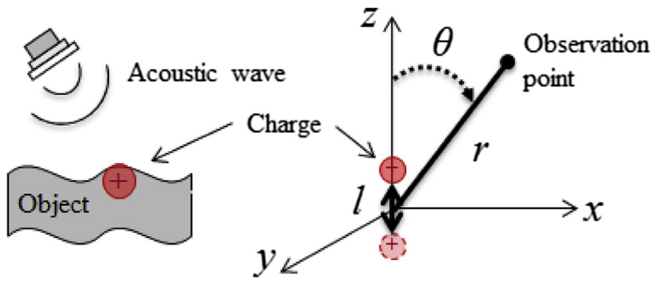

Fig. 1. Concept and coordinate system for an electric field induced by charge oscillation.

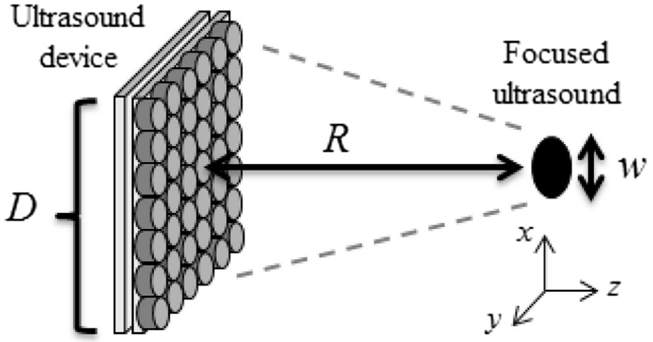

Fig. 2. Relationship between device array size and the diameter of the focal point.

Experiment method

In the present study, it was necessary to use low-frequency sound waves in order to focus ultrasonic waves with sufficient amplitude to trigger localized oscillation due to the relationship between Eqs. (1) and (2). In order to achieve such conditions, the compact ultrasound device fabricated for the study in Ref. [17] was used. The size of the array was $D = 170$ mm, with 285 individual ultrasonic oscillators arranged within a rectangular region, with a maximum generated force at the focal point of 16 mN. This device can be modulated at DC − 1 kHz by turning the 40 kHz ultrasonic signal on and off. It is therefore possible to trigger oscillations at low frequencies while maintaining the degree of focus and without deteriorating the essential qualities of the ultrasonic waves. The experimental system used for evaluating the focused ultrasonic waves is shown in Fig. 3.

First, a hole of 10 mm diameter was drilled in a plate, which was then mounted on the front of a speaker. The speaker was then placed at a distance of 170 mm from and facing the ultrasound device in order to evaluate the characteristics of the focused ultrasonic waves (Fig. 3(a)). This speaker was moved using an x–y stage (range: $40 \times 40\ \text{mm}^2$; 2 mm pitch) to evaluate the degree of focus of the focused ultrasonic waves. In order to evaluate the oscillation due to the radiation of the focused ultrasonic waves on the sample object surface, the ultrasound device was installed 170 mm from and facing the sample object (Fig. 3(b)). A vinyl chloride sheet (thickness 10 μm; size $250 \times 250\ \text{mm}^2$) was used as our sample object, which was irradiated by the focused ultrasonic waves. The displacement distribution (measurement range: 50 mm) in the vicinity of the focal point of the ultrasonic waves was measured using a line laser displacement sensor (LJ-G200, Keyence Corp.).

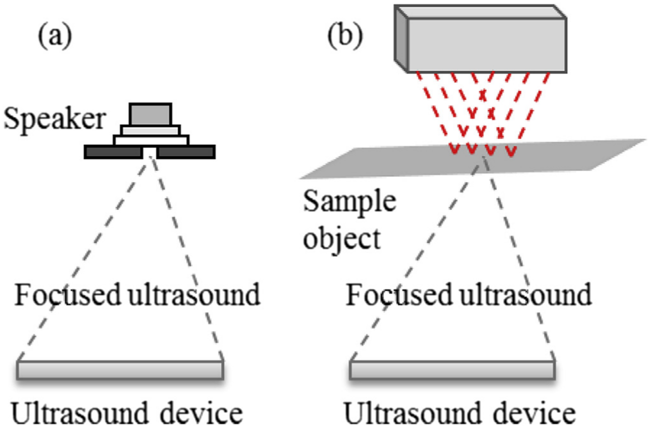

Fig. 3. Experimental setup for (a) characterizing a focused ultrasound wave and (b) evaluating the induced excitation.