Study on Charge Oscillation-Induced Low-Frequency Electric Field

Kazuya KIKUNAGA, Hiroshi YAMASHITA, Masahiro EGASHIRA and Kazuhiro NONAKA
Measurement Solution Research Center
National Institute of Advanced Industrial Science and Technology, AIST
807-1, Shikumachi, Tosu, Saga 841-0052, Japan
k-kikunaga@aist.go.jp

Abstract—Electric field induced by charge oscillation has been investigated by simulation of the electric field distribution using the finite-difference frequency-domain method. In addition, the electric field was induced by spatial oscillation of a sample to which a DC voltage was applied. The simulation and evaluation of the electric field verified that the efficiency for inducing the electric field has a proportional relationship with the amplitude of displacement of a charged object, and detecting the electric field from the top to the side of the object is possible.

Keywords—static electricity; charge oscillation; electric field; low frequency

I. INTRODUCTION

In recent years, automated manufacturing has been promoted at production sites in the manufacturing industry to enhance production efficiency. Because the transportation process plays an important role in achieving high efficiency, soft materials such as rubbers are used to prevent damage to products and half-finished products, or resin and ceramic materials are used from the perspective of attrition, including friction. Therefore, products and half-finished products are repeatedly in contact with and separated from highly insulating materials, causing higher rate of static electricity generation. In particular, in the electronics industry where low-voltage driving has been advanced for devices, static electricity has become a serious problem. Further, in the automated production process, electrostatic hazard is an extremely serious problem because it is difficult to identify the location that causes the problems because many charged materials exist. A large amount of time and wasteful cost is needed to investigate the causes that result in low productivity. For this reason, the scale of the market for static electricity-related products has been reported to top eight billion dollars by 2015, along with the rapidly growing needs for countermeasure for electrostatic problems.

Monitoring static electricity in various places at the production sites is extremely difficult. One of the reasons is that only very few static-electricity measuring equipment is available in relation to the environment and situations, which does not improve productivity. To cope with the miniaturization of electronic devices, reduction in static discharge resistance, and complicated manufacturing apparatuses, development of a technology that can easily measure static electricity at production sites, which involves many spatial restrictions, is strongly desired. Various types of surface potential sensors have been developed to measure static electricity that targets electrostatic field and capacity. However, they suffer from the disadvantage in which the measurement range may depend on the distance from the sensor to the object because these sensors measure the signals detected at the sensor side. Thus, static electricity may not be detected in some cases if the sensor is installed at a distance because it is prone to the effects of ground wire in the vicinity, and measurement from the lateral direction is difficult. For these reasons, common surface potential sensors must be installed closer to the objects to measure static electricity in a pinpoint manner. However, installing the sensors closer to the object is not preferable in some cases because products and apparatuses continuously move at the production sites, causing unexpected movement of the products by electrostatic power and adhesion of foreign particles. Therefore, a static-electricity measuring technology that can limit the measurement area without putting the sensors closer to the objects at the production sites is required.

We have developed a technology to measure static electricity by detecting the change in the signal by applying acoustic oscillation to charged objects. In the present work, we examine the characteristics of low-frequency electric field induced by charge oscillation to develop sophisticated static electricity measurement using this approach.

II. EXPERIMENT METHODS

A. Electric field induced by charge oscillation

To describe the concept of charge-oscillation induction, we consider a case where an object to be measured with positive (or negative) electric charge physically oscillates. In this case, the static electric charge also oscillates spatially with the object. As the spatial position of the charge varies over time, electric field is induced around it. The dipole radiation theory is applied as electric field is induced by charge oscillation. If electric field $E$ [V/m] created by moving charge particles...
with charge \( q \) [C] is laid on the polar coordinates shown in Fig. 1 and the movement direction of the charge particles is in the \( Z \) direction, the generated electric field can be expressed as follows:\textsuperscript{[14]}

\[
E = \frac{1}{4\pi \varepsilon_0} \frac{q}{r^2} \mathbf{e}_r + \left\{ \frac{q l}{2\pi \varepsilon_0 r^2} \left[ (1 + jkr) \cos \theta \mathbf{e}_r + \frac{q l}{2\pi \varepsilon_0 r^2} \left[ \cos \theta + jkr + (jkr)^2 \right] \sin \theta \mathbf{e}_\theta \right] e^{-jkr} \right\}
\]  

(1)

In this equation, \( \varepsilon_0 \) [F/m] is the permittivity in vacuum, \( l \) [m] is the displacement of the charge particles, \( r \) [m] is the distance from the charge particle to the observing point, \( k \) [m\(^{-1}\)] is the wave number (\( k = 2\pi f / c_0 \)), \( f \) [Hz] is the number of charge particle oscillation, \( c_0 \) [m/s] is the speed of light in vacuum, \( j \) is an imaginary number, \( \theta \) [rad] is the slope relative to the Z axis, and \( \mathbf{e}_r \) and \( \mathbf{e}_\theta \) are the vectors along the \( r \) and \( \theta \) directions, respectively. In this case, the first factor in the right-hand side of the equation indicates the electrostatic field. Here, we exclude the terms derived from the electrostatic field because our study aims to measure the static electricity due to the oscillating charges. The other terms related to \( e^{-jk\theta} \) indicate the electric fields that vary over time. Because simultaneously finding all solutions is very complicated, we assume that the frequency is approximately 100 Hz, and the distance to be observed is one wavelength or shorter to simplify the calculation. The prevailing term for the generated electric field (quasi-electrostatic field) is expressed as follows:\textsuperscript{[14]}

\[
E = \frac{1}{4\pi \varepsilon_0} \frac{q l}{r^2} \left( 2 \cos \theta \mathbf{e}_r + \sin \theta \mathbf{e}_\theta \right) e^{-jkr}
\]  

(2)

Charge \( q \) is obtained by measuring the electric field. This quasi-electrostatic field, which have lost its wave motion property, exhibits characteristics similar to those of the electrostatic field.

B. Electromagnetic field calculation within low-frequency domain

The finite-difference time-domain (FDTD) method is a well-known analysis method for electromagnetic field using the Maxwell equations. However, as the difference between the time and spatial domains is calculated by the FDTD method, the number of time steps required for the calculation time is inversely proportional to the frequency, and huge amount of time is required in the low-frequency domain. Therefore, the finite-difference frequency-domain (FDFD) method in which the frequency is given and the time factor is excluded is adopted in this study. In the FDFD method, the calculated difference in the spatial domain of a balanced field with fixed frequency is substituted through temporal differentiation of the Maxwell equations by designating the frequency. In addition, the discretized spatial differentiation is converted into a simultaneous linear equation. Therefore, performing calculations is possible regardless of the frequency. We perform the calculations under the following conditions:

the size of calculation area is \( 200 \text{ mm} \times 200 \text{ mm} \) (X-Z plane), the cell size is 5 mm, the frequency domain is from 100 Hz to 10 MHz (wavelength is from 3,000 km to 30 m), the dipole length is 1 to 20 mm (Z direction), and the applied voltage is from 10 mV to 10 V.

C. Experiment methods

The experimental apparatus is shown in Fig. 2. The system consists of an excitation device to oscillate the samples and an electric field-measuring device. A small vibration generator (512-A/EMIC) connected to a function generator is used to generate oscillation. The vibrating part and insulating support stand to fixed the samples are directly connected to a 200-mm-long stainless bar, allowing for electromagnetic noise from the vibration generator. Here, metal flat plates (made of copper with a thickness of W:10 mm × D:10 mm × H:0.3 mm), where DC voltage ranging from 0 to 200 V are applied, are used as samples with static electricity. The dimensions of the samples are set up from 100 \( \mu \)m to 1 mm by providing feedback to the vibration generator using a laser displacement meter. The oscillation frequency is set up from 10 Hz to 1 kHz. In addition, EFA-300 of Narda S.T.S. is used, which is calibrated as an electric measuring device for low-frequency electric field. The electric measuring device is installed at a vertical (Z-axis) or horizontal (X-axis) position 50 mm from the samples.

III. EXPERIMENT RESULTS AND DISCUSSION

A. Frequency dependence of low-frequency electromagnetic characteristics

The simulation results of the electric and electromagnetic distribution of the electric dipole obtained by the FDFD method is shown in Figs. 3(a) and (b). Here, the calculation is performed under the following conditions: the size of calculation area is \( 200 \text{ mm} \times 200 \text{ mm} \) (X-Z plane), the cell size is 5 mm, frequency range from 10 MHz to 100 Hz, and dipole of 10 mm length (Z direction) is applied a voltage of 1 V. Fig. 3(a) shows that while the magnetic field distribution exhibits a stationary shape laterally looped from the dipole at 10 MHz, it transforms into a non-stationary shape as the frequency becomes lower. From this result, we believe that measuring the magnetic fields in the low-frequency domain is difficult because the magnetic loop based on alternating current is not formed in a linear manner. Fig. 3(b) shows that the electric...
The electric field distribution is formed into a stationary shape even if the intensity ratio in the vertical and horizontal directions exhibits no change according to each frequency. From this result, we understand that the generation efficiency of the electric field induced by charge oscillation does not depend on the frequency. Further, it can be measured in all directions, including the vertical and horizontal directions.

The frequency dependence of the electric field is shown in Fig. 3(c), which is measured at \( X = 0 \) mm and \( Z = 50 \) mm by applying vibration at 150 Hz and 1 kHz, respectively, in the samples to which a DC voltage of 100 V is applied using the experimental apparatus shown in Fig. 2. The characteristics shown at the lower part in Fig. 3(c) are those of the electric field measured when the grounded samples vibrate, and the small signals at 150 Hz and 1 kHz correspond to the noise of the oscillation generator. In addition, the electric fields at 150 Hz and 1 kHz, which are larger than the noise, were measured in the samples to which voltage was applied. The result suggests that inducing electric field by spatial oscillation of the samples is possible, which proves that an electric field with the same frequency as the vibration frequency of the sample has been generated.

**B. Amplitude dependence of electric field intensity**

Fig. 4(a) shows the simulation results of the electric field distribution when the electric dipole length is varied in the range from 5 to 20 mm at a frequency of 100 Hz using the FDFD method. The electric field intensity increases as the electric dipole length becomes longer while the shape of the electric field distribution is maintained. This result indicates that the longer the electric dipole length is, the higher is the electric field generation efficiency. The electric dipole is supposed to correspond to the amplitude of the charge oscillation.

By oscillating the sample with superimposed voltage from 35 to 350 Hz, as shown in Fig. 2, the electric field intensity is measured using an electric field sensor installed in the sample at \( X = 50 \) mm and \( Z = 0 \) mm, whereas the amplitude is measured by a laser displacement meter installed on the vertical direction of the sample. The results of the standardized electric field intensity and sample amplitude displacements at each frequency are shown in Fig. 4(b). From these results, we determine that the electric field intensity and amplitude displacement have a direct proportional relationship at any frequency. Thus, we obtain a result similar to that of the simulation. Further, we determine that the accuracy is lower at 350 Hz because the amplitude displacement is small. In the case of actual object oscillation, the higher the oscillation frequency is, the smaller is the amplitude displacement where a sample can physically move. Moreover, we prove from the result of the frequency dependence that the electric field generation efficiency does not depend on the frequency. Oscillating the object in the low-frequency domain is effective, where the amplitude displacement increases when static electricity measurement is performed using the proposed method.

**C. Quantitative property of static electricity measurement based on electric field**

Fig. 5(a) shows the simulation results of the electric field distribution when the applied voltage is varied in the range from 100 mV to 10 V at a dipole length of 5 mm and frequency of 100 Hz. From these results, we determine that the electric field distribution changes according to the voltage level applied to the dipole, and the vertical and horizontal aspect ratio of the shape of the electric field distribution becomes smaller as the applied voltage reduces. This result indicates that the higher the applied voltage is, the stronger is the electric field distribution intensity.

Figs. 5(b) and (c) show the measurement results of the electric field on the X, Y, and Z axes when a sample with an
applied voltage that ranged from 0 to 200 V is oscillated with an amplitude of 1 mm and a frequency of 100 Hz. Fig. 5(b) and (c) show the results of the measurement from the vertical (X = 0 mm and Z = 50 mm) and horizontal (X = 50 mm and Z = 0 mm) directions of the sample. Electric field is detected only in the Z-axis direction in the upper measurement shown in Fig. 5(b), whereas it is detected only in the X-axis direction in the lateral measurement shown in Fig. 5(c). Equation (2) shows that the induced electric fields have azimuthal components. Figs. 5(b) and (c) also show that the electric field and the applied voltage have a direct proportional relationship at Z and X axes. Thus, we believe that the applied voltage in the simulation correspond to the level of the static electricity, which indicates that quantitative evaluation of static electricity is possible by oscillating the charged objects and measuring the size of induced electric field. Even though the measurement accuracy of the results obtained in the study is approximately 5%, we expect further improvement in the accuracy by significantly enhancing the sensitivity of the electric field sensor.

On the other hand, the ratio of the electric field size at the vertical direction to the horizontal direction is approximately 3:2. However, the ratio should be 2:1 based on equation (2). Because the ratio is considered as a term only for the quasi-electrostatic field in equation (2) in this case, the calculated contribution ratio is at approximately 50%. Therefore, we believe that considering the other terms (induced field and radiation field) in real situation is necessary. Further, the electric dipole is used as an approximate replacement for the charge oscillation in the simulation. Because the dipole formed by both positive and negative charges oscillates in the case of the electric dipole whereas the single charge oscillates in the case of charge oscillation, we believe that some processes such as calibration are required because these oscillations are different. Further, we expect the electric field generation efficiency to be significantly different. However, quantitatively evaluating the static electricity is possible by calibrating the actual measured values because theories and the experiments in

(a) Electric field (simulation)

(b) Vertical direction

(c) Horizontal direction

Fig. 5. (a) Simulation of the generated electric field by the applied alternating voltage. Relationship between the sample with applied voltage and the electric field measured from (b) vertical (X = 0 mm and Z = 50 mm) and (c) horizontal (X = 50 mm and Z = 0 mm) directions of the sample.

IV. Conclusion

In the present study, we have examined the characteristics of the electric field based on both theories and experiments to develop a technique to measure the static electricity induced by charge oscillation. Using the FDFD method in the field calculation, we have proven that simulating the low-frequency electromagnetic field distribution in a short time is possible. Further, the FDFD method is a dominant tool for recognizing the electric and electromagnetic fields. In addition, we have proven from the combined results of the simulation and experiments that the electric field can be suited for charge oscillation-induced measurement, the field generation efficiency can be maximized by increasing the amplitude of the oscillation, the frequency in the low-frequency domain can be used to increase the amplitude, and the electric field induced by the charge oscillation can be detected in all directions.

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