Visualization of Dielectric Barrier Discharge Sound Field in Atmospheric Pressure by Novel Method

T. Nakamiya1, F. Mitsugi, Y. Iwasaki, T. Ikegami, R. Tsuda, Y. Sonoda

1Graduate School of Industrial Engineering, Tokai University, Kumamoto, Japan
2Graduate School of Science and Technology, Kumamoto University, Kumamoto, Japan

Abstract: The sound signal generated by the Dielectric Barrier Discharge was detected by a Fraunhofer diffraction effect and the discharge sound was analyzed. The strong sound area is located around the electrodes and different with the frequency components of the discharge sound. The sound signal from discharge device may be useful to examine the discharge phenomena around the electrodes.

Keywords: Discharge sound, Fraunhofer diffraction, Computerized tomography

1. Introduction

DBD (Dielectric Barrier Discharge) is widely used for ozone synthesis, pollution control including the removal of the environmental pollutant, surface modification, biomedical application and so on. Future applications may include their use in greenhouse gas control technologies.

The characteristics of DBD are mainly examined by applied voltage, discharge current, and luminescence. There is almost no research paper that uses the discharge sound to examine the electrical discharge phenomenon such as DBD. We have examined the sound signals which are emitted from the discharge area [1-4]. Because the sound signals contain about the information of discharge and atmospheric condition around the discharge.

However, it’s not easy to detect the sound signal in plasma reactor by the conventional condenser microphone technique. Therefore, we have developed a new diagnostic method, in which sound wave is measured by an optical sensor based on a Fraunhofer diffraction effect between the sound wave and laser beam. The light diffraction technique, which we call the “Optical Wave Microphone (OWM)” technique, is an effective sensing method to detect the sound and is flexible for practical uses as it involves only a laser and simple lens system [5-8]. This technique is also very useful to detect the sound wave without disturbing the sound field. Moreover, OWM can be applied for the visualization of sound field by computerized tomography (CT) because the ultra-small modulation by the sound field is integrated along the laser beam path [9,10]. The two-dimensional discharge sound distribution (Reconstruction image) can be obtained by inversely projecting the data. The projection data can get by moving the discharge device mounted on the stage.

2. Fundamental equation of OWM-CT

Figure 1 shows the schematic diagram of OWM. When the probing laser beam crosses perpendicular to refractive index change with sound wave which passes along x0 direction at the beam waist plane (x0,y0,0), diffracted waves are generated. The penetrating beam with the diffracted waves propagates through a Fourier optical lens (lens 2) and reach the observing detector which is set at Fraunhofer diffraction region or at the back focal plane (x0,y0) of the Fourier lens (lens 2).

If the sound pressure distribution is integrated along the s-axis for the interaction length (L) between the sound wave and the laser beam, the equation (1) can be obtained [4,11].

\[
I_{ac} = \frac{2P_L}{\pi w_f^2} \left[ k_i (\mu_0 - 1) \exp \left[ -\left( u^2 + (u - \theta)^2 \right) \right] \right] \sin \omega_p t \int_{s_1}^{s_2} \bar{p}(s) ds
\]

(1)

where:
- \(P_L\): laser power;
- \(w_f\): beam waist in the back focal plane of lens 2;
- \(u\): normalized x-coordinate (s/w_f);
- \(\theta\): normalized wave number (k_iw_f/2);
- \(\omega_p\): angular frequency of refractive index change;
- \(k_i\): wave number of laser;
- \(\mu_0\): refractive index of atmosphere;
$\gamma$: specific heat ratio;  
$p$: atmospheric pressure;  

CT method can reconstruct a cross-sectional image of the sound field using projected data from many directions of at least 180 degrees. The two-dimensional sound field $\delta(x_0, y_0)$ along the propagation direction of the $z_0$ is the subject area of our present research. The projected data $D(r, \varphi)$ which is the detected signal can be written as the following equation.

$$D(r, \varphi) = \int S(x', y') ds$$

where $r$-$s$ coordinates are rotated by $\varphi$ from the $x_0$-$y_0$ coordinates [4]. The reconstruction image can be obtained by inversely projecting the data to $x_0$-$y_0$ coordinates, in which the filtered back-projection method and Lamp filter function were used as the reconstruction algorithm [12].

3. Experimental Procedures

Figure 2 shows a schematic view of the experimental setup to detect the sound signal from the DBD. The device consists of two electrodes buried under $\text{Al}_2\text{O}_3$ ceramic substrate (15 mm in width, 37 mm in length, and 1.25 mm in thickness). The discharge device, which was mounted on a stage, was set up inside the acrylic chamber. The chamber was filled with atmospheric gas of Ar. The probing laser beam (685 nm, 28 mW, 2 mm in diameter) of OWM passed through above the discharge device. The sound signals of transmitter crossed the laser beam between the diode laser and Lens 1. The diffracted laser beam was performed the optical Fourier transform by the Lens 1 and guided to the photodiode detector by the multimode optical fiber. The diameter of the laser to reach to the optical fiber was adjusted by the beam expander (Lens 2 and Lens 3). The acoustic signals detected by OWM were stored in the digital oscilloscope (Tektronix TDS3034) and analyzed. To obtain projection data for CT analysis, the discharge device was rotated in the $\theta$ direction and moved toward the $x$ direction.

The glow-like discharge appeared on the surface of the discharge device. When the high voltage was applied to the electrodes, the discharge current appeared and the discharge sound was generated. The discharge sound was detected by the OWM. Figure 3 (b) shows the FFT (Fast Fourier Transform) spectra of voltage wave-form of OWM. It contains many frequency components such as 25, 50, 74.5 kHz. These values are almost same with the fundamental, 2nd and 3rd harmonics frequency of applied voltage frequency.

Figure 4 shows the projection data of discharge device. The surface of discharge device was away 1 cm from the probing laser beam ($z=1$ cm). The sound field was rotated and moved in the $x$-$\theta$ direction while the probing laser was fixed. Although the sound field is rotated and moved, the measurement result is the same as that by scanning the laser beam and the detection device. From Fig. 3, it can be expected that the sound field has an obvious peak on the axis. The sound field at the $x$-$y$ plane was visualized by a CT method.

4. Results and discussion

Figure 3 (a) shows waveforms of OWM measured in the Ar atmosphere. Amplitude and frequency of the sine curved applied voltage were fixed at 6 kV and 25 kHz.
The rotation step angle was set to 20 degrees from 0 to 180 degrees, and the driving range in the x direction was from -25 mm to 25 mm with the step length of 5 mm.

Fig.4 Projection data of the sound emitted from the discharge device using OWM-CT.

Figure 5 (a) shows reconstructed images of sound field at two-dimensional x - y plane emitted from discharges in Ar. Top view of electrode for the coplanar dielectric barrier discharge device is illustrated in Fig.5 (b). The high voltage electrode appears on the surface. In Fig.5 (a), this electrode is located 0 in x-coordinate and 0 to 4.5 mm in y-coordinate. The spread and blurred emission was observed in the discharge of Ar atmosphere. The sound field along the y direction was the strongest at just above and both sides of the top electrode. The similar results were confirmed in air and N2 which were reported in previous work [3,5]

Fig.5 (a) The reconstructed image of sound field at x – y plane emitted from discharges in Ar by the OWM-CT. (b) View of the electrodes for the coplanar dielectric barrier discharge device. The figures of (a) and (b) are the same reduced scales.

Fig.6 Reconstructed images of sound field at x – y plane emitted from discharges in Ar. (a) 25kHz component (b) 50kHz component (c) 74.5kHz component

Figure 6 shows the reconstructed images of sound field of each frequency components such as 25, 50 and 74.5 kHz. The intensity of the each frequency components were obtained by the FFT analysis shown in Fig. 3 (b). Figure 6 (b) shows the sound distribution of 50 kHz frequency components. The strong sound field appeared
on the right side of top electrode. This frequency component of 50 kHz (Twice of applied voltage frequency) concerns plasma conditions such as the density of ions, the electric field, the emission and so on. On the other hand, the strong area of 25 and 74.5 kHz components appear around the top electrode of discharge device.

5. Conclusions
The OWM-CT was applied to detect the sound field from the coplanar dielectric discharge in Ar. Visualization of discharge sound field of each frequency components was performed. The distribution of each frequency components in discharge sound is important to understand the plasma conditions.

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7. References