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Force at spark discharge in pin-to-plate system

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Abstract

We have investigated whether any force is generated by a spark discharge in a pin-to-plate system. Because it was difficult to measure the force directly over a short sparking period, three independent methods were employed to evaluate the magnitude of the force indirectly: (1) Axial vibration was observed for the pin electrode supported flexibly by a cantilever to the axial direction at the spark discharge that occurred periodically. The force was implicitly calculated in the case that the calculated vibration agreed with the measured. The result indicated that the force was almost 0 N during the spark period. The vibration was generated not by the force at the spark discharge but by alternative force of the Coulomb force at the period of no discharge and reaction force due to the ionic wind at the corona discharge. (2) A similar investigation was conducted whether the vibration magnitude depended on the spark current based on the assumption that the force at spark discharge depends on the spark current if any substantial force is generated at the spark discharge. We deduced that the force was not generated during the spark period and it was irrelevant to the spark current. (3) We made a hypothesis that axial vibration of the pin electrode could be observed if the spark discharge did not take place but the varying voltage was applied of which pattern was common with that with the spark discharge. To confirm the hypothesis an experiment was conducted with two parallel-connected pin-to-plate systems, the air gap of one system was slightly shorter than the other. The axial vibration was observed even in the system that the spark discharge did not take place and the vibration agreed also with the calculated. These three results suggested that no substantial force was generated at the spark period.

Keywords: Gas discharge; Corona; Spark; Electrostatic force; Ionic wind

1. Introduction

The mechanics of a pin-to-plate gas discharge system have been investigated previously [1–4], because these are an important basis for many industrial applications, such as a pump and a fan without moving parts [5], micro-machines [6], an electrostatic inkjet printhead [7], and electrostatic microspray [8,9]. It is well known that the gas discharge in the pin-to-plate system is categorized with three patterns, no discharge, corona discharge, and spark discharge in accordance with increase of the gap voltage [2]. At voltages lower than corona onset, no substantial current flowed in the air gap. Coulomb attractive force results between the pin and the plate electrode. The force is proportional to the square of the voltage and independent of polarity. The force becomes large in accordance with the increase of the pin diameter and the decrease of the air gap. However, above the threshold voltage, a discharge current on the order of several microamperes is measured, and at the same time, weak luminescence is observed at a tip of the pin electrode. That is, corona discharge takes place. The current and luminescence are stable. In this mode, a relatively large repulsive force compared to the Coulomb force occurs due to the ionic wind generated by the migration of charged ions in air. It depends highly on the applied voltage but it shows little dependence on the air gap, the pin diameter, and voltage polarity. If the applied voltage is further increased, sparking and sound suddenly occurs and high current flows in the gap. Because the power capacity of the power supply is restricted in the actual system, the spark discharge is not continuous but intermittent. Although substantial efforts have been devoted to understand the electrical characteristics of a spark discharge [10], almost nothing has been reported on its mechanics. The objective of the present work is to

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clarify whether any force that can be utilized for micro-actuators is generated during a spark discharge.

2. Implicit method

2.1. Experimental procedure

Fig. 1 shows the experimental set-up used to deduce force implicitly for the case of an intermittent spark discharge. A wire (0.5 mm in diameter) made of stainless steel was hung perpendicular to a steel plate (100 mm in diameter). The wire was connected to the free end of the cantilever plate made of stainless steel. A stiffness k of the cantilever at the point of attachment of the wire was 2.68 N/m. The gap between the wire and the plate was adjusted using a mechanical stage attached at the back of the plate electrode. High voltage was applied to the gap by a DC power supply (Matsusada Precision Inc., HVR-10P (positive) and HVR-10N (negative), $0\sim\pm 10$ kV adjustable, maximum current 0.15 mA). Voltage was determined by a calibrated potentiometer within the power supply and measured directly with a high voltage probe (Iwatsu, D-401). Current was measured via the voltage drop across a current-shunt resistor. If the applied voltage was increased above a critical value, for example 7 kV in case of 4.0 mm air gap, spark discharge took place. At the same time vertical vibration of the cantilever was induced. At the voltage just over the critical voltage, although the occurrence of the spark discharge was unstable and random, the cantilever began to vibrate in the vertical direction. If the applied voltage was increased, the spark discharge became periodic as shown in Fig. 2. The amplitude of the vibration was large, in the order of 1 mm, which was about 10 times as large as the static displacement under the corona discharge. Pulse width of the spark discharge was 0.5–5 ms, which was short compared to the period of the free vibration, in the order of 100 ms. The vibration coupled with the occurrence of the spark discharge. The spark discharge took place almost when the pin electrode approached to the plate electrode, because the critical voltage of the spark discharge was low when the air gap was small. The vibration at the free end of the cantilever was measured by a laser displacement meter (Keyence Corporation, LK-080). Transducer signals of the vibration, the gap voltage, and the current were sent to a digital oscilloscope. The surfaces of the electrodes were polished before every experiment to prevent oxidation and chemical deposition on the tip of the discharge electrode due to gas discharge.

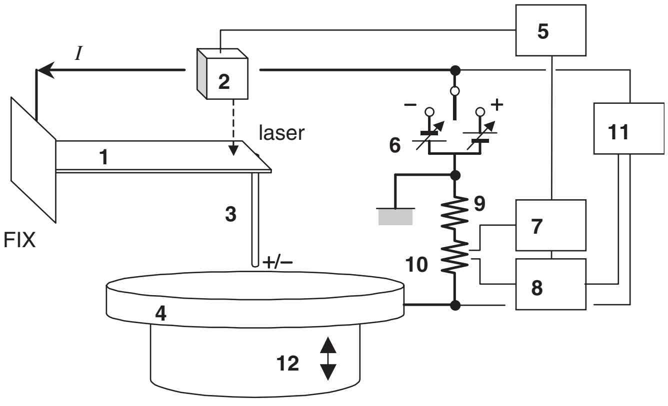

Fig. 1. Experimental set-up. (1: stainless steel plate, cantilever T0.1/L100/W20 mm, 2: laser sensor, 3: pin electrode, stainless steel ϕ 0.5 mm, 4: plate electrode ϕ 100 mm, 5: laser displacement meter, 6: DC high voltage power supplies, 7: oscilloscope, 8: DC volt meter, 9: resistor, 10: shunt resistor, 100 Ω, 11: high voltage probe, 12: mechanical stage).

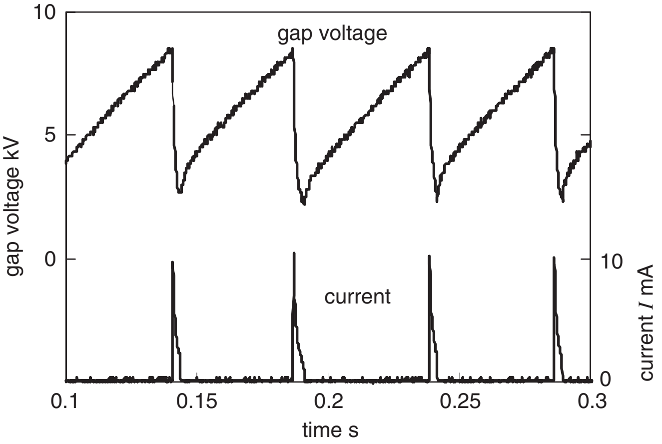

Fig. 2. Gap voltage and current at spark discharge (positive, 4.0 mm air gap, 500 kΩ resistance).

Because the spark discharge is intermittent, the following implicit method was adopted to deduce the vertical force applied to the pin electrode at the spark period. The vibration of the cantilever connected to the pin electrode was modeled as a single-degree-of-freedom system with respect to the vertical displacement z; the upper direction is designated to be positive.

$$m\ddot{z} + c\dot{z} + kz = F_z(t),$$

where m is an equivalent mass of the pin electrode and the cantilever, c is a viscous damping coefficient, k is the stiffness of the cantilever, $\ddot{z} = d^2z/dt^2$, $\dot{z} = dz/dt$, and t is time. The stiffness k was statically measured dividing weights put on the free end of the plate by the static displacement measured by the laser displacement meter, and the other vibration parameters m and c were determined from the free vibration response. F_z is the vertical force acting on the pin electrode. The force during no discharge and the corona discharge has been measured by the separate static experiment. That is, the electrostatic force to the pin was derived multiplying the measured displacement and the stiffness of the cantilever. On the other hand, the magnitude of the force at spark period had been unclear. It was determined implicitly as summarized in Fig. 3, i.e., the numerical calculations were conducted to calculate vibration responses with assumed forces during the spark period. Then averaged deviations between the measured and calculated vibration responses were calculated and the force corresponding to the minimum