Repeating Vortices Induced by the Dielectric Barrier Discharge Plasma Actuator

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Abstract

A typical dielectric barrier discharge (DBD) plasma actuator is initiated by a burst signal of sinusoidal wave in quiescent air and induced flow field is visualized with the help of smoke flow visualization technique. The DBD plasma actuator generates a starting vortex when initiated by a typical continuous signal. A burst signal results in continuous generation of vortical structures calling as repeating vortices. During unsteady operation formation of dipole like structure is also observed. The purpose of this paper is to understand and study the vortical structures induced by the DBD plasma actuator in burst mode/unsteady operation.

Keywords: *DBD plasma actuator; Starting vortex; Repeating vortices; Dipole.*

I. INTRODUCTION

Dielectric barrier discharge (DBD) plasma actuator has gained much popularity as an active flow control technology for aerodynamic flow control due to its several advantageous over conventional flow control such as thin and light weight, completely electronic, no moving part, less power consumption, fast response, low cost, simple geometry, no passage or cavity or holes etc. [1-3]. The capability of DBD plasma actuators for flow control applications has been demonstrated by various researchers around the world few of them are: laminar boundary layer separation control over an airfoil [4], excitation of stationary cross flow modes in a Mach 3.5 boundary layer [5] and streamwise vortex generation [6].

When DBD plasma actuator is initiated a starting vortex is generated. The vortical structure originates from the edge of exposed electrode which develops with the time and travels along and away from the wall towards the encapsulated electrode and finally it disappears and flow field transforms into a wall jet. The starting vortex attains self-similarity when the maximum velocity induced by the actuator attains a steady state. The core of vortex scales with $t^{2/3}$ and travels at an angle of 31° to the surface of wall [3]. The similarity solutions for both the steady laminar and turbulent wall jet is available in [7]. A theoretical study has been done by Cantwell [8] for transient motions of an incompressible viscous starting jets. In a numerical study of transient motion of wall jet, Conlon and Lichter [9] demonstrated the formation of dipole. They revised the criterion of negative vorticity for dipole formation earlier given by Yushina [10] and concluded that the presence of moving separation point occurs concurrently.

In the present work, the DBD plasma actuator is operated in quiescent air with a burst of sinusoidal signal to repeat the transient motion or starting process. Consequently, the vortices are continuously generated by the DBD plasma actuator. The knowledge about the behavior of flow field induced by the actuator is important to understand the flow control phenomenon. The aim of this paper is to study the vortical structures induced by the DBD plasma actuator in burst mode operation observed in preliminarily stage of experiments.

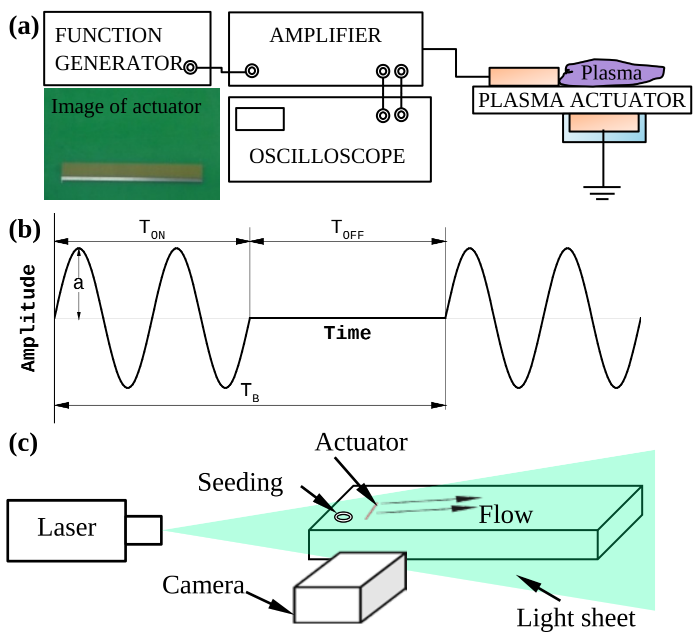

Fig. 1 Schematic of (a) experimental set-up for initiating DBD plasma actuator, (b) applied burst signal and (c) experimental set-up for smoke flow visualization of flow field induced by the DBD plasma actuator.

II. METHODOLOGY

A schematic of experimental set-up for initiating the DBD plasma actuator and applied signal is shown in Fig. 1(a) and (b) respectively. The DBD plasma actuator is initiated by a high speed high voltage power amplifier (Trek 20/20C-HS). The power amplifier provides a gain of 2000 times of input signal. The input signal to the power amplifier is supplied with help of a function generator (Agilent 33220A) and the applied signals are monitored by a digital storage oscilloscope (Agilent DSO-X 2012A) with the help of a high voltage probe (Pintek 39 pro) and an inbuilt voltage monitor of power amplifier. The DBD plasma actuator used in this study has been fabricated in institute printed circuit board (PCB) fabrication laboratory on a 165×145 mm^2 PCB made of flame retardant-4 having a dielectric constant, $\varepsilon = 4.7$. The PCB acts as a dielectric and copper is used to etch the electrodes on the surface of the dielectric material. The electrodes of actuator are 10 cm long and are placed asymmetrically on each surface of 1 mm thick dielectric with no gap between the electrodes. The exposed and encapsulated electrodes are 2.5 mm and 10 mm wide respectively. The encapsulated electrode is encapsulated with the help of few layers of polymide kapton tape.

A high speed imaging is required to capture the starting vortex generated by the DBD plasma actuator. However, by operating a DBD plasma actuator in burst mode the vortical structure are generated continuously which in turn makes it possible to capture the induced vortical structure with low speed imaging facility also. A schematic of experimental facility for flow visualization is shown in Fig. 1(c). The flow visualizations are carried out inside a closed rectangular chamber having length, width and height of 85 cm, 36 cm and 46.5 cm respectively. The smoke particles of Dioctyl Sebacate ($C_{26}H_{50}O_4$) liquid are generated by Oxford atomizing seeding generator. The smoke particles are illuminated by a Nd:YAG laser manufactured by New Wave Research, Inc. and images are acquired by a PCO sensicam SVGA camera with the help of Nikon 180mm f2.8 lens. The images are captured at a frequency of 8 Hz with resolution of 1280 x 1024 $pixel^2$ and in real units 24 pixels are equal to 1 mm.

The actuator performance mainly depends upon geometrical parameters, electrical properties of electrode and dielectric material and applied electrical signal. For a given actuator, it is the applied electrical signal which governs the performance. Keeping waveform unaltered, a continuous electrical signal constitutes of two variables, i.e. amplitude and frequency of applied signal while a burst signal along with the above mentioned two variables brings two more variables one is 'ON' time (T_{ON}) and another is burst frequency (f_B). The actuator is operated at constant applied potential of 14 kV peak to peak and frequency of 2 kHz with $T_{ON} = 145$ ms and 'OFF' time, T_{OFF} is equal to $T_{ON}/4$ which corresponds to burst frequency, $f_B = 1/T_B \approx 5.5$ Hz (where, $T_B = T_{ON} + T_{OFF}$ is burst period) and duty cycle, $\alpha = T_{ON}/T_B = 80\%$. The time period, T_{ON} corresponds to the time required to achieve the steady state (i.e. wall jet like flow) which is determined from high speed schlieren visualization system by operating the actuator with a continuous signal of same amplitude and frequency.

III. RESULTS AND DISCUSSION

In this section we will present the flow visualization images of transient motion induced by the DBD plasma actuator. The images are acquired for only a single test condition (see, section II). All the images are captured sequentially in a single shot by setting a burst of 100, 200 and 300 images. Since, the flow visualization has been carried out with a low speed imaging facility there is no basis for choosing frame rate for recording the images. Our aim was to capture the flow field and to conform the continuous generation of vortices in burst mode, exact instantaneous time was not a matter of concern and due to the fact it has to be noted that the images shown in present work are not sequential. The vortical structures are successfully captured and in each shot of image burst several vortices are found. The capability of low speed imaging to capture the vortical structure and presence of number of vortices in each image burst confirmed the repeated phenomenon of formation of consecutive vortical structures. An applied burst signal contains N number of burst period (T_B) and each burst period produces a single vortex. Hence, a burst signal with N number of burst period generates N number of vortices consecutively.

The flow visualization images are divided in three categories: (i) vortex formation and development, (ii) formation of dipole like structure and (iii) concurrent vortices. The vortical structure rolls up and develops with time [3] hence larger structure corresponds to a larger time.

Fig. 2 shows the formation and development of vortex at four different and arbitrary time intervals t_1, t_2, t_3 and t_4 ($t_1 < t_2 < t_3 < t_4$) and time t_1 is the smallest time interval after initiation of plasma actuator. The vortex core locations are marked with the help of a red color dot. The vortex travels along the surface and grows with the time. The circulation and generation of vorticity of the vortex is attributed to velocity gradient due to vertical entrainment and horizontal flow [3].

Fig. 3 shows the formation of dipole and their development for four different time t_1, t_2, t_3 and t_4. The circulation is marked with red color circles. It is the relative magnitude of positive and negative vorticity which controls the formation of dipole [9]. The criterion for dipole formation is available in Yushina [10] and Conlon and Lichter [9]. The dipole like structure shown in Fig. 3 is observed randomly. Whalley and Choi [3] found no evidence of dipole formation for the cases they considered for investigation.

Two consecutive vortices that occur concurrently are shown in Fig. 4 for two different arbitrary time t_1 and t_2. At time t_1, we can see that near the exposed electrode vortex is about to form and downstream vortex core is about to cross the image window. At time t_2, the core of both the preceding and succeeding vortex are present. In comparison to that of image at t_1 succeeding vortex has formed and preceding vortex core have travelled smaller distance. The two vortices occur concurrently due to the difference between actuation of actuator (which depends upon T_{ON} and f_B) and time taken by the vortex to disappear (which depend upon vortex core velocity). In other words it is due to the time scale difference between the actuation of DBD plasma actuator and the vortex dynamics.

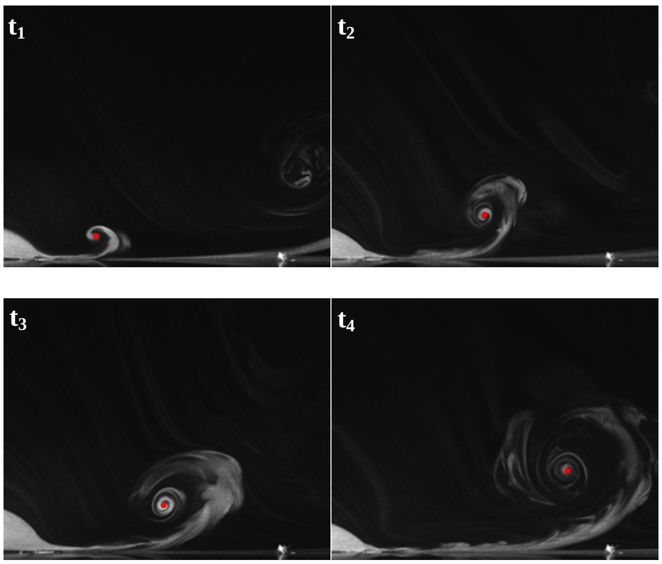

Fig. 2 Vortex formation and development at arbitrary time t_1, t_2, t_3 and t_4 where, $t_1 < t_2 < t_3 < t_4$.

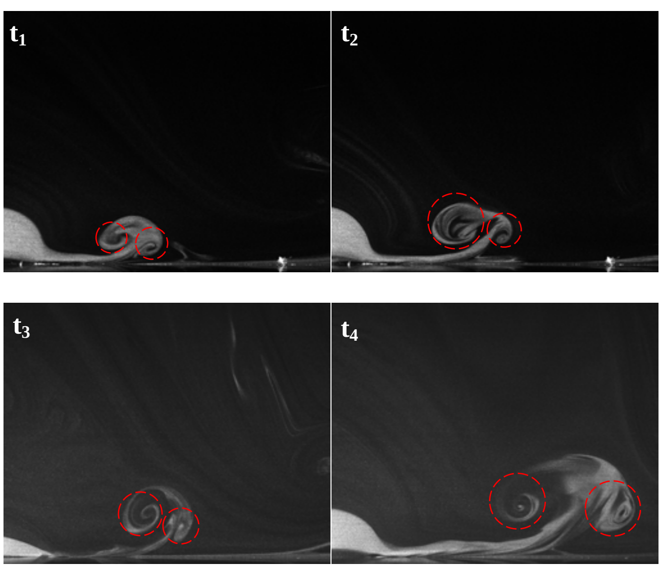

Fig. 3 Existence of dipole like structure at arbitrary time t_1, t_2, t_3 and t_4.

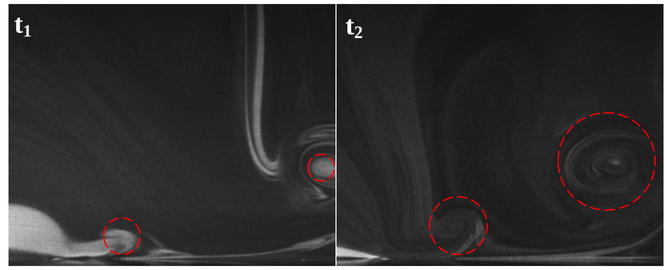

Fig. 4 Two consecutive vortices at arbitrary time t_1 and t_2 occurring concurrently.

IV. CONCLUSIONS

The DBD plasma actuator is operated with a burst of electrical signal and the resultant flow field induced by the actuator is visualized by smoke flow visualization technique. The flow visualization result reveals the continuous generation of vortical structures. It also reveals the existence of dipole like structure. Each burst of applied electrical signal generates a single vortical structure and N number of burst produces N number of vortices. The frequency of vortex generation can controlled by the burst frequency, f_B. The flow visualization of formation of various flow structure presented in this study needs a detailed investigation, both qualitatively and quantitatively.

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