Plasma assisted Turbulent Flow Separation control over a backward facing step

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This paper describes the use of Dielectric Barrier Discharge (DBD) plasma actuators to control the flow separation over a backward facing step. The two geometries of plasma actuator tested were linear and serpentine. The control was conducted for inflow velocity of 13.4 m/s with Re = 1.7×10^4 based on step height and freestream velocity. The actuators were placed in a co-flow arrangement. We found that the linear actuators do not show any reduction of reattachment point when run on continuous mode (1 kHz, 24 kVpp). However, for an amplitude modulated signal with a waveform 1 kHz, 28 kVpp and amplitude modulated at 125 Hz, the linear actuators showed a 14% reduction in reattachment point. For the AM mode serpentine actuator gave an impressive 31% reduction in reattachment location. These data along with the floor pressure data after the step clearly depict the benefits of using serpentine DBD actuator over linear actuators as an active flow control device.

I. INTRODUCTION

Flow over a backward facing step has been a widely studied problem to understand flow separation due to its simplicity. However, our present work entails flow separation control using plasma actuators. DBD plasma actuators have been used to control flow separation around cylinders [1], airfoils [2], backward facing step [3-4], etc. Free shear layer formed in a flow over backward step is unsteady in nature and is governed by Kelvin – Helmholtz instability. It was found that the flow can be best controlled when the forcing frequency and the natural flow instability frequencies are same [3-4]. The instabilities generated in a backward facing step are governed by the Kelvin Helmholtz instability mechanism. The growth and decay of these instabilities can be manipulated by plasma actuators. Plasma actuators control the flow separation by breaking down the streaklines in the incoming flow. This leads to formation of new small scale structures which perturb the free shear layer and make the instabilities grow faster. This allows the flow to rapidly turbulize and reattach at an earlier point. This makes the separation bubble smaller and leads to drag reduction. Although linear DBD actuators have been used in the past no work has been done using serpentine DBD actuators to control flow around backward facing step. This paper will present results for both linear and serpentine DBD actuators and show that serpentine actuators perform far better than linear DBD actuators for the same power consumption.

Most flow control mechanisms rely on perturbing the base flow at frequencies close to the instability modes present in the flow. Hasan [5] found that for laminar separation in a backward step, two kinds of instability modes are present namely the shear layer mode and the step mode based on momentum thickness and step height. He showed that forcing the shear layer at Strouhal number of 0.012 based on momentum thickness and 0.185 based on step height, would provide an effective flow control mechanism. This idea was also incorporated by Sujar-Garrido, P., et al. [3]. They found that the best forcing frequency is 125 Hz for Re_θ of 1400. Chun and Sung [6] also found that the forcing frequency of St_θ of 0.01 gave the least reattachment length. Different forcing methods have been studied to control the flow separation. This includes acoustic forcing [5-7], oscillating flap [8-9], pulsed blowing [10], plasma actuators [3,4,11] etc. Here, plasma actuators will be studied as a flow control device.

This paper is organized in the following manner. Section 2 will describe the experimental setup for our problem. Section 3 will present PIV results and pressure data. Finally, section 4 will derive a brief conclusion and suggest future research pathways.

II. Experimental Setup

The experiment is carried out in a low speed open wind tunnel. The test section depicted in Figure 1 shows side view of the backward step along with the actuator and tripping tape. The test section cross-section was 50.8 × 152.4 mm^2 and the length extended 254 mm upstream of the step and 406.4 mm downstream of the step. The tripping tape was placed 127 mm from the step and had a cross-section of 2×0.5 mm^2. This allowed the incoming boundary layer to be fully turbulent at the upstream of the step. The backward step is made of transparent acrylic to facilitate visualization and based on the geometry provides a smooth transition of the flow from the nozzle to the test section. The step height was chosen to be 19 mm. The freestream velocity was measured by a hot wire anemometer before conducting a PIV study. The wind tunnel was set at 960 rpm which generated a velocity of 13.4 m/s (30mph). This freestream velocity and step height, sets the Reynolds number at 1.7×10^4. The turbulent intensity of the wind tunnel is measured to be 1%.

In order to study the flowfield PIV measurements are taken around the step. The PIV window is set such that it captures the entire reattachment bubble. The particles were visualized using an Nd YAG laser of 532 nm

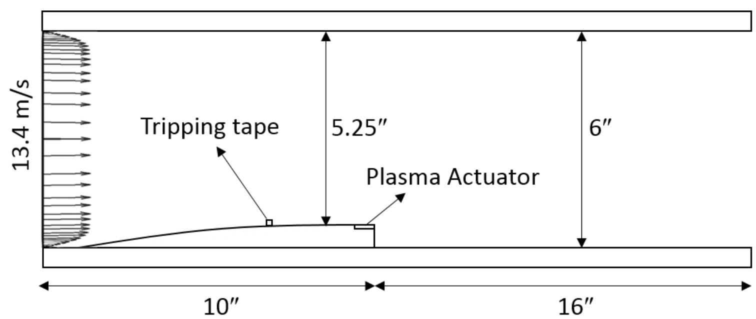

FIG 1: Schematic of the wind tunnel test section along with the backward step and actuator

wavelength and a high speed camera. The central plane of the step is only studied for our present work. The wind tunnel was seeded for particle image velocimetry measurements, using fog juice which generated particles of size 4 μm. The data was processed using LaVision Davis 7.2 software is used to process the data. A phantom high speed camera is used to capture the images and has a resolution of 1024×1024 $pixel^2$. The interrogation window was set at 150×100 mm^2. Pressure data was collected using a 16 port Scanivalve pressure transducer. The pressure taps were made on the floor after the step each with an equidistant spacing of 6.35 mm starting from the step. Since only 16 ports could be measured necessary adjustments were done such that a smooth pressure profile could be obtained.

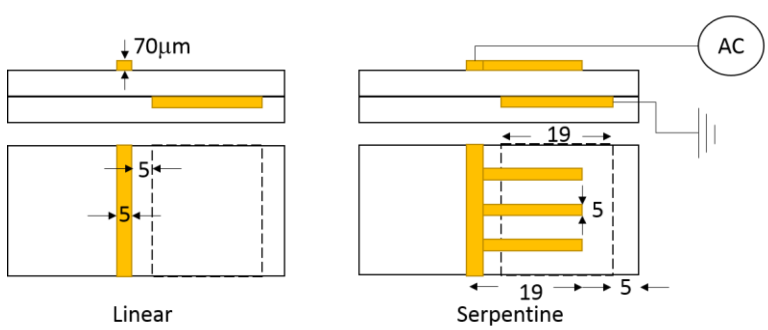

FIG 2: Schematic of the linear and serpentine actuator (dimensions in mm)

Two types of plasma actuators were tested which includes linear and serpentine comb actuator (from here on referred as serpentine actuator). As depicted in Figure 1 the actuators are flush mounted near the step. The electrode configuration is shown for both linear and serpentine actuators in Figure 2. The encapsulated electrode is grounded and the exposed electrode is powered. The actuator is constructed using PMMA as the dielectric material of thickness 3.125 mm. In order to conduct our study two different voltage signals were used. The input signal waveform is depicted in Figure 3. The input signal is supplied using a high voltage TREK amplifier. The actuators were tested using an input signal of frequency 1 kHz and voltage 24.4 kV_{pp} and an amplitude modulated signal formed using a HF input signal (1 kHz, 28 kV_{pp}) and a 50% modulation signal (125 Hz). From here on we shall refer to the former signal as continuous signal and the later as the AM signal. It should be noted that the continuous signal couldn't be used for a higher voltage due to current limiting of the TREK amplifier. The modulation frequency was chosen to be 125 Hz, after testing a range of frequencies varying from 30 Hz to 150Hz. It was found that 125 Hz corresponds to best reduction of the reattachment length. This corresponds to a Strouhal number based on step height of 0.178. The actuators generate a wall jet of maximum velocity of 3.5 m/s for the continuous signal and 2 m/s for the AM signal. The velocity field for the serpentine and linear actuators are depicted in Figure 4. It should be noted that the serpentine actuator and the linear actuator have different flowfield structure. A detailed study on flow structures created by serpentine actuators can be found in Durscher and Roy [12].

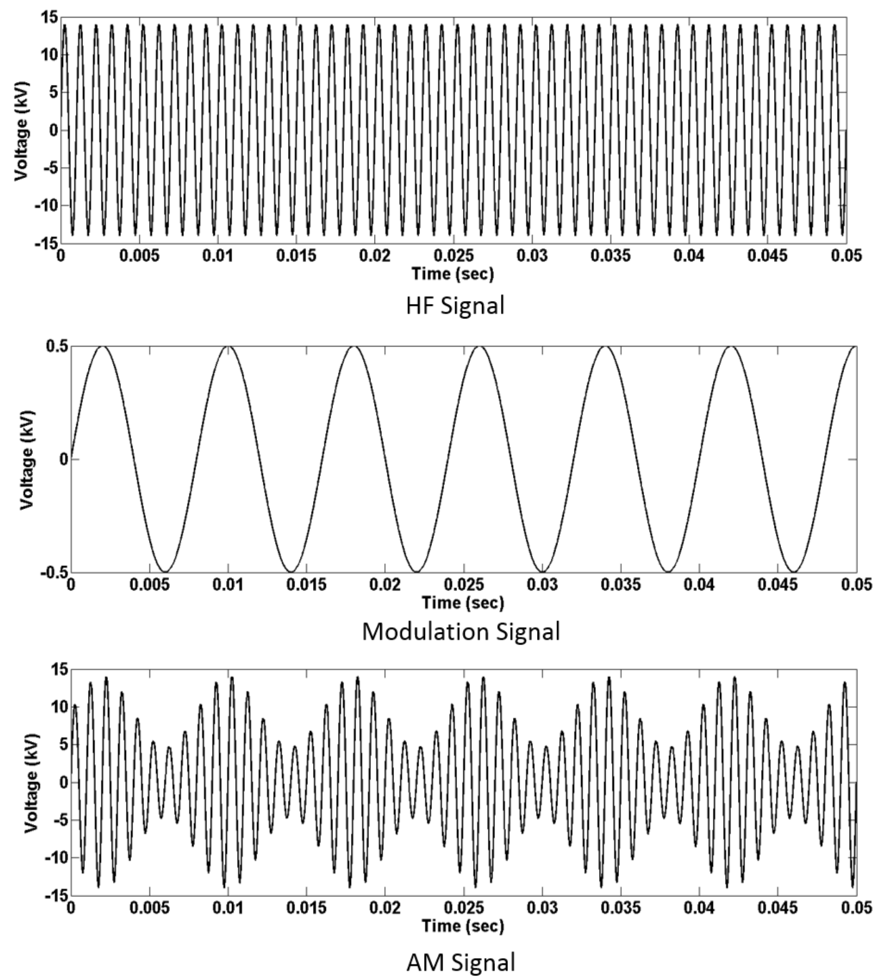

FIG 3: Amplitude modulated waveform

III. RESULTS

Figure 4 shows the gauge pressure data along the floor at different *x/h* locations. There are four different cases compared with the baseline case and we can clearly see a shift in the pressure lines towards the step. In the figure linear and serpentine actuators are compared along with the continuous and AM mode of operation. The pressure up to the bubble reattachment is displayed. For the continuous mode the linear actuator (Lin1) shows no reduction,

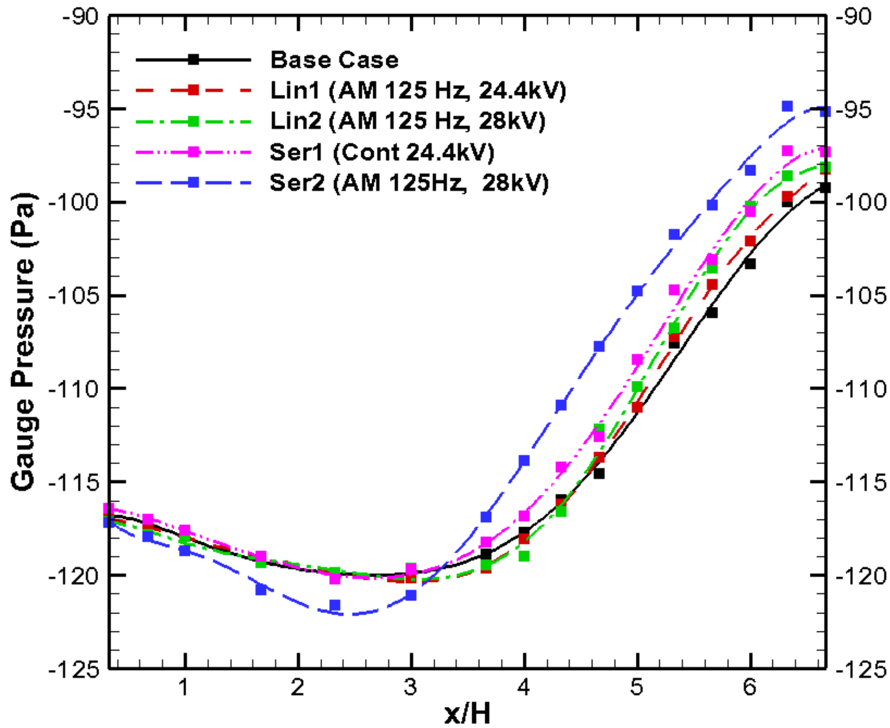

FIG 4: Variation of pressure along the floor after the step using linear and serpentine plasma actuators

however the serpentine actuator (serp1) shows almost 7.8% reduction in pressure based on the base pressure far from the step of 100 kPa. This reduction is further enhanced by using the AM mode which reduces the pressure by 13.6% for the serpentine actuator (serp2) and about 3% (lin2) for the linear actuator. This is attributed to the fact that the AM mode and three dimensional perturbations of serpentine actuators [12] excite the secondary instabilities and allow nonlinear streak growth. The serpentine actuator creates counter rotating vortices which can penetrate beyond the buffer layer. Thus along with the AM mode excitation, these vortical structures break the streak lines and increase the turbulent intensity of the flow which results in shorter reattachment length. PIV study of the linear and serpentine were performed for the 28kV_{pp} AM mode and we can clearly see in Figure 5 that the bubble size is reduced by almost 14% for the linear and 31 % for the serpentine actuator case. The dotted lines correspond to the zero streamwise velocity. The mean flow is obtained using average of 1000 images. The plasma actuated cases bring the bubble center closer to the floor which in turn reduces the magnitude of the negative pressure inside it. The change of bubble size for serpentine actuator can be related to the large change in pressure depicted in Figure 4.

IV. CONCLUSION

The effect of actuator location is not studied since it is reported in literature that the best flow control can be obtained when the actuator is placed right before the step [3]. The location of the reattachment has been successfully reduced up to 31% using the serpentine actuator. Running the actuators in the amplitude modulated mode not only works better than the continuous mode but is also known to consume less power. Thus operating the serpentine plasma actuator in AM mode will provide the most efficient flow control mechanism when compared to all the cases studied here.

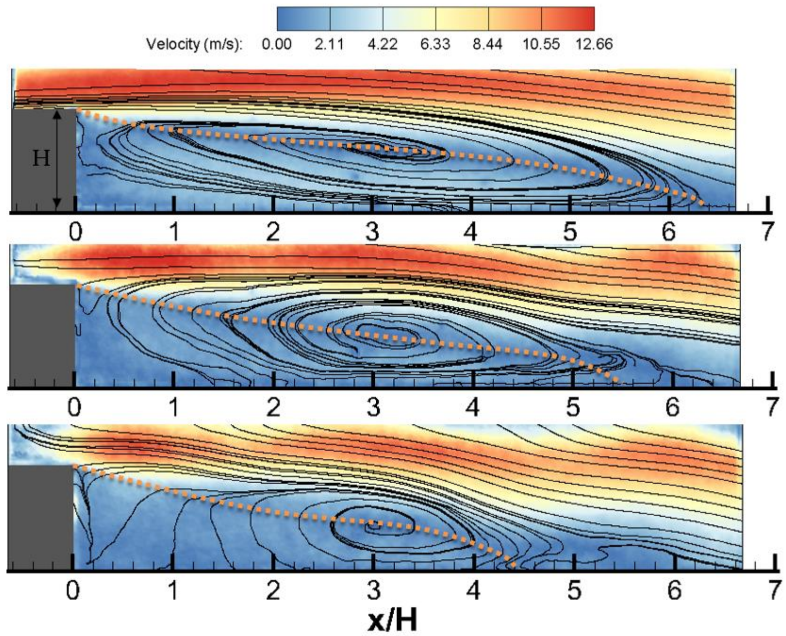

FIG 5: Time averaged Streamwise velocity contours after the step (top) Baseline, (middle) step with linear actuator, (bottom) step with serpentine actuator

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