

Active Vortex Generators Using Jet Vectoring Plasma Actuators

Michael Bolitho and Jamey Jacob

Oklahoma State University

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ABSTRACT

Vortex generators, both active and passive, have been shown to be useful flow control devices on aircraft for both separation control and to maintain uniform flow over sections of the wing by energizing the boundary layer, particularly control surfaces. Meanwhile, plasma actuators have been used to delay separation by adding momentum to the boundary layer. Linear plasma actuators have been shown to be an effective arrangement of the plasma actuator for several applications of aerodynamic flow control, primarily separation. The annular plasma actuator, or plasma synthetic jet actuator (PSJA), has also been shown to be effective as a zero net mass flux jet. Similar to the annular plasma actuator, the linear thrust vectoring plasma actuator can be used to create a wall-normal jet, but with vectoring capability. It is shown that by varying parameters of the input signal, the strength of the dielectric barrier discharge, as well as the direction of the jet produced, can be controlled. The type of jet produced by unsteady actuation is shown to be affected by the pulsing frequency, and the angle of jet created is shown to be affected by the driving frequency and the duty cycle. By arranging the plasma actuators in a thrust vectoring configuration and pulsing them, vortices are created and shed. When this is applied to cross-stream flow, the vortices shed by the thrust vectoring plasma actuators reduce separation, similar to a pulsed vortex generator jet. The concept is demonstrated for low speeds and potential applications are discussed.

INTRODUCTION

Plasma actuators, also known as discharge plasma, dielectric barrier discharge, and glow discharge actuators, are a relatively recent development that offers unique options in flow control applications [1]. A number of re-

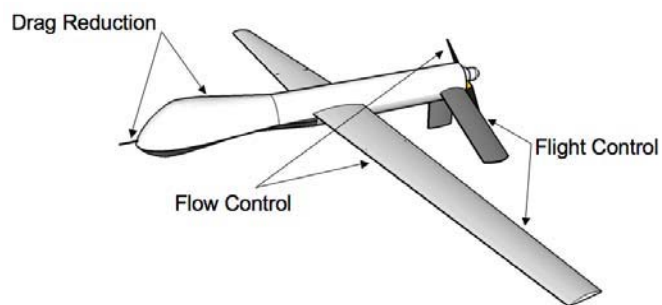


Figure 1: Possible regions of use for plasma actuators on a UAV.

searchers have investigated plasma actuators over recent years, and the present paper discusses further investigations from a perspective of developing plasma actuators for use on small unmanned aircraft.

Of relevance here, conventional synthetic jet actuators are another type of fluidic device that generates ZNMF jets formed from the working fluid of the system in which they are applied, albeit from purely mechanical methods. These have been shown to be useful as active flow control devices [2]. They are commonly produced by using an oscillating diaphragm mounted in a cavity that is embedded beneath the surface of interest. The diaphragm is driven in such a way that fluid is alternately sucked into then ejected from the cavity in a periodic manner and the jet is created by the advection and interaction of discrete vortical structures generated in this cycle.

While the above two devices operate on fundamentally different physical mechanisms, the resulting fluid flows have many similar characteristics. The similarities increase when one generates a synthetic jet flow field with plasma actuators arranged in a synthetic jet geometry [3]. This pa-

per presents results for jet vectoring linear plasma actuators used as flow control devices. The flow field induced by the thrust vectoring plasma actuator is similar to the above two devices, except it creates a two dimensional jet which can be vectored away from the normal.

Benefits of plasma actuators include:

- Low power
- High frequency response
- Flush mountable
- Flexible

However, they have a low output authority, which requires judgment during application. Figure 1 shows possible uses for plasma actuators on a typical UAV.

PREVIOUS WORK

A number of researchers have investigated the use of plasma flow control (PFC) devices for flow control applications, such as separation control and as replacements for conventional control surfaces [4, 5, 6, 7, 8, 9]. This includes the development of novel geometries such as chevrons that may be used to develop cross-stream flow structures. Recently, the PI has developed the plasma synthetic jet actuator (PSJA) that can serve as a replacement for traditional synthetic jet actuators [10, 11]. A benefit of the PSJA over conventional synthetic jet actuators is that since they are flush mounted, they can be installed virtually anywhere. Also, they are low power devices using power in the range from 1-100 Watts based upon actuator size, geometry, and input parameters such as applied voltage, pulse frequency and duty cycle.

In addition to the cited examples, plasma actuators have been used to control a number of complex 3D unsteady flows. Asghar and Jumper examined the use of PFC for phase synchronization of the vortex streets from multiple cylinders [12]. They were effectively able to modify the natural out-of-phase vortex shedding and force an in-phase vortex shedding behavior for a pair of cylinders. Likewise, Siegenthaler *et al.* investigated the use of a single PFC actuator to control the coherent structures in a planar, weakly compressible, free shear layer [13]. Results include McLaughlin *et al.* where PFC was used to control the structure of the Karman vortex street by using feedback results from measurements of the shedding frequency to drive the actuator frequency [7]. Corke *et al.* demonstrated the use of plasma actuators as virtual flaps and slats for airfoil flow control [4]. Actuators located at the leading edge can control separation while actuators placed at the trailing edge can control lift.

Enloe *et al.* presented numerous findings on the physics of plasma actuators [14, 15]. Based on large scale integral measurements of thrust output, voltage and plasma emission measurements, and simulations, the authors make several interesting conclusions, including that the power input, P , to the plasma is nonlinear with the voltage drop, ΔV , across the dielectric, and that both the maximum induced velocity, u_{max} , and thrust, T , are proportional to

input power, such that $T \propto u_{max} \propto P \propto \Delta V^{7/2}$. In addition, their measurements found that the plasma has complex spatial and temporal structure, the creation of plasma occurs on both the positive and negative slopes of ΔV and is dependent upon $d\Delta V/dt$. Also, thrust is greater for a “positive” waveform as opposed to a “negative” waveform, even though the bulk plasma structure is the same. This observation implies that bulk heating is not the mechanism for thrust generation, as some researchers have previously speculated (the “positive” waveform appears to produce a more uniform discharge). Their final conclusion is that the plasma induces an electrostatic body force on the surrounding fluid that is proportional to the net charge density and the strength of the electric field, as $\mathbf{F} = -(\epsilon_0/\lambda_D^2)\phi\mathbf{E}$ such that the net charge density can be expressed as a function of the electric potential, where ϵ_0 is the permittivity of free space and λ_D is the Debye length, respectively. Presently, this model serves as the basis for much of the current plasma actuator development.

There are several operational areas where plasma actuators may be used on aircraft, including drag reduction, control and maneuverability, noise reduction, propulsion, and wake vortex mitigation. These are discussed in turn below.

USE AS CONTROL EFFECTORS Previous researchers have investigated the use of flow control over 2D airfoils under various conditions as discussed above. This will be expanded by examining the flow over 3D bodies, namely airfoils and other lifting devices. Experiments will primarily be conducted in the UK wind tunnel laboratory, supplemented by flight testing where appropriate. These include a wide array of testing facilities across the range of Re and subsonic Mach numbers, and offer numerous options in terms of plasma actuator control schemes and input powers. Test models include both external (airfoils/wings, fuselages) and internal (ducts) flows. As an example of experiments under current investigation, Figure 2 shows the location of plasma actuators placed on a wing of finite aspect ratio at $Re \sim 10^4$. In the current results, each actuator was actuated independently (1 actuator at a time). Using PIV, the downwash and tip vortex strengths were recorded as a direct measured of the change in lift. Results for the wake are shown in Figure 3a, while relative changes in the

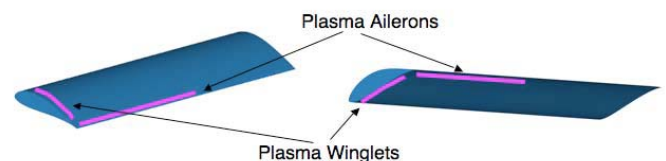
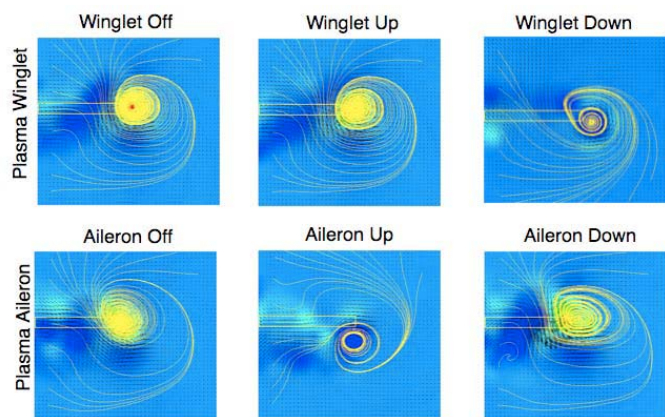
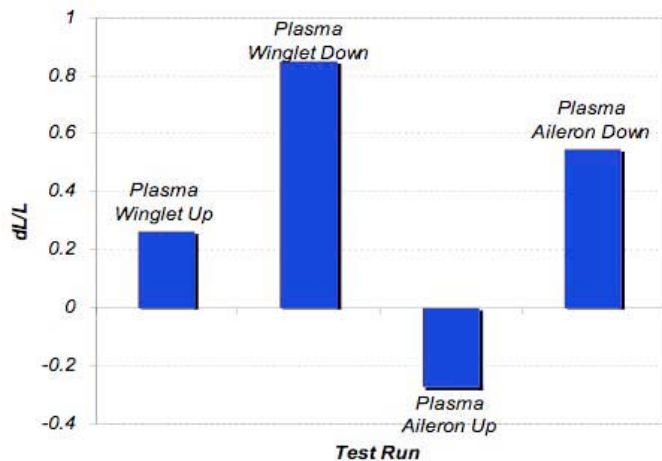


Figure 2: Plasma actuators placed on various portions of a wing for control.



(a)

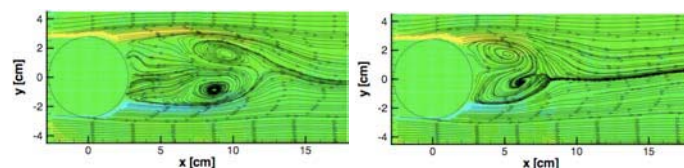


(b)

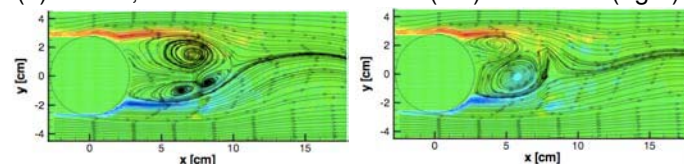
Figure 3: Change in lift of the wing. (a) Wake vortex characteristics. (b) Change in lift compared to baseline.

lift are shown in Figure 3b as obtained using the vortex strength and the Kutta-Zhukhovski theorem. Positive increases in lift up to 92% are observed in 3 cases, while a decrease in lift is measured in a single case. For the plasma aileron, useful for maneuvering, the total change in lift is approximately 60% of the baseline lift in the upward position and -30% in the downward position.

DRAG REDUCTION Previous studies have shown the effectiveness of plasma actuators for drag reduction, particularly in separated flows whether on bluff bodies or streamlined shapes. For example, Figure 4 shows the impact of an actuator on a cylinder at low Re , greatly reducing the overall wake of the body and reducing drag. However, this effectiveness decreases as Re increases, requiring continual embiggening of the plasma actuator power input to keep the effect prominent. Effectiveness of linear steady actuators on cylinder drag reduction as a function of Re are shown in Figure 5 [16]. Though the effectiveness can be increased at higher Re by pulsing the actuators and leveraging the unsteady vortex generation ability of the actuators [17], another option is to leverage the geometric design of the actuator to push the flow out of the near wall boundary layer [10].



(a) $Re=5,000$ with actuator off (left) and on (right).



(b) $Re=10,000$ with actuator off (left) and on (right).

Figure 4: Effects of plasma actuator on a circular cylinder wake.

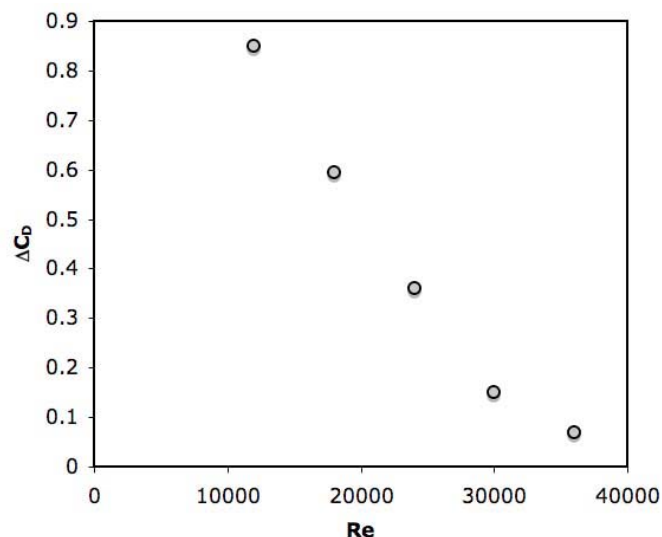


Figure 5: Reduction in C_D on a cylinder vs. Re . (Corke - cite).

VECTERING PLASMA ACTUATORS

COST-BENEFIT ANALYSIS For an in flight plasma actuator to be a viable design option, some of the following criteria must be as good or better than that of a conventional system:

- efficiency
- maneuverability
- control
- weight
- cost
- reliability and range of operating conditions

Currently, none of these parameters offer significantly better performance than a traditional system. Weight, cost and reliability concerns will improve as research into plasma technology continues. However, two primary benefits are readily apparent with plasma actuators: improved efficiency through drag reduction and possible lift increases and enhanced maneuverability. These are discussed briefly below in the following sections.