Laminar Flow Control of a Flat Plate Boundary Layer Using Dielectric Barrier Discharge Plasma

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To Thomas Alfred Gibson (dec.), Rodney Thomas Gibson, & Benjamin John Chartier;

my three favourite engineers.

Summary

The drag developed on an object as it moves through a fluid comprises of a number of components arising from various and differing fluid phenomena. For aerodynamic bodies such as aircraft, one of the most dominant components of the total drag force is that arising from shear interactions between the surface of the object and the fluid. In steady, cruise conditions this shear-induced skin friction drag can account for almost 50% of the total drag force on the body and hence this is the reason much interest surrounds the minimisation of this component.

Laminar Flow Control (LFC) is the field of aerodynamics focused on minimising skin friction, or viscous drag. The viscosity of a fluid, and the shear interactions between the layers of fluid and the aerodynamic body give rise to a boundary layer, a region of fluid with diminished fluid velocity and momentum. Laminar Flow Control aims to minimise the momentum deficit within the boundary layer by manipulating the flow within and encouraging favourable flow conditions to exist and be maintained. In essence, Laminar Flow Control attempts to maintain laminar flow within the boundary layer, improving the stability of the flow, delaying the onset of turbulence and the formation of a turbulent boundary layer that develops significantly more drag than an equivalent laminar structure.

A number of techniques exist for controlling and maintaining laminar flow within a boundary layer. Examples include compliant surfaces, acoustic arrays and suction, and all share the common trait of complexity, which to date has limited the application of such systems in the real world. In the search for simpler Laminar Flow Control technology, attention has been turned towards Dielectric Barrier Discharge (DBD) plasma actuators as a possible alternative. Through the formation of a small volume of plasma, these actuators are capable of producing an electrostatic body force that can couple with the surrounding air and bring about a jetting effect without the addition of mass. This jetting effect, if controlled effectively, can potentially favourably augment a boundary layer flow and lead to a delay in transition.

The work discussed in this thesis represents a contribution to the field of DBD-based Laminar Flow Control. The aim was to further investigate the potential of plasma actuators for improving the hydrodynamic stability of a boundary layer and hence contribute to the limited published data pertaining to this field. The research involved the development of a DBD-based LFC system in which plasma actuators were used to augment the most fundamental of boundary layer flows, the flat plate, Blasius-type. By measuring the augmentation to the velocity profile of the boundary layer brought about by the LFC system, the stability of the flow was able to be investigated and hence the feasibility of the technology determined.

The plasma actuators utilised in this research were designed such that control could be achieved over the shape of the induced jetting profile. To minimise adverse interactions with boundary layer flows, the plasma actuators were designed so that the magnitude and position of the maximal induced jetting velocity could be controlled. After consultation of the literature, novel actuators utilising orthogonally arranged electrodes were conceived and tested in a parametric study. Through variation of the distance to which the exposed electrode sat proud above the surface of the actuator, in addition to variation of the applied voltage, it was found that the desired control over the induced jet could be attained, leading to the identification of two mechanisms through which the DBD-based LFC system could be tuned. The details of the design and development of these orthogonal actuators and the effect of the electrode height on the jetting characteristics of the devices can be found in Gibson et al. (2009a) and Gibson et al. (2009b).

After identifying suitable and novel actuator arrangements, a tuning strategy was conceived to hasten the development of the LFC system. Rather than implementing the actuators and measuring the response of the boundary layer to the plasma first, Linear Stability Theory was instead used to identify desirable boundary layer augmentation objectives for the LFC system. Linear Stability Analyses (LSAs) were performed on a number of idealised boundary layer flows, obtained from curve fitting analytical functions to published DBD-augmented boundary layer data, as well as from boundary layer theory. The LSAs were conducted using an Orr-Sommerfeld Equation solver developed as part of this research, which utilises a finite differencing scheme. The outcome of this comparison process was that the developed DBD-based LFC system was used to attempt to augment the boundary layer such that the flow attained an asymptotic suction velocity profile, which would give the boundary layer a limit of stability almost two orders of magnitude greater than that of the base flow, and hence significant robustness to transition.

The conceived DBD-based LFC system was implemented into a Blasius-

type boundary layer which was formed over the Flat Plate Rig (FPR) designed and developed as part of this research. Initially a single actuator was utilised, positioned just upstream of the location of the critical Reynolds Number (limit of stability) of the flow. Due to the design of the FPR and the actuators utilised, it was possible to study the response of the layer to the plasma with and without a mild suction effect, introduced through a $5mm$ wide slot that was required for operation of the actuator. This mild suction effect was measured to be approximately $4Pa$, and by itself was found to be insufficiently strong enough to augment the flow such that it attained the characteristics of a boundary layer with uniform wall suction. With the FPR, measurements of the velocity profile of the boundary layer with and without flow control were made around the critical Reynolds Number location of the flow ($80000 < Re_x < 120000$), which allowed the changes to the stability of the flow to be studied.

As discussed in Gibson et al. (2012) the initial results of the DBD-based LFC system showed that the plasma was adversely affecting the stability of the flow. Subsequent tuning of the system was therefore performed through variation of the applied voltage of the actuator. From this tuning it was found that an actuator operated with an applied voltage of $19.0kV_{pp}$ (referred to as a *low-voltage* actuator) in conjunction with the mild suction effect, produced boundary layer characteristics akin to those of a flow exposed to uniform wall suction. In addition, an actuator operated with an applied voltage of $21.4kV_{pp}$ (referred to as a *high-voltage* actuator) was found to adversely affect the stability, even more so in the absence of the mild suction effect. The single low-voltage actuator was found to be able to maintain uniform wall suction-like characteristics for $50mm$ beyond the trailing edge of the encapsulated electrode. This finding pertaining to the use of the low-voltage actuator highlighted the potential of a single DBD device to develop uniform wall suction-like characteristics with only a mild suction effect through a single slot, and hence in a less complex fashion than conventional suction systems.

An attempt was made to maintain the favourable benefits of the single, low-voltage actuator by using two such actuators placed in series. However, the effect of this combined double-actuator/suction system differed only slightly from the suction-only system (with two slots instead of one), meaning that in this configuration, the use of the plasma was somewhat superfluous. Hence it could be concluded from the results of the research that a single low-voltage actuator operated in conjunction with a mild suction effect is more effective as a LFC system than a single mild-suction slot, but a combined double-low-voltage actuator/suction system is no better than a simpler and less energy consuming double-mild-suction slot system. It is, however, anticipated that through the undertaking of future works, utilising additional actuators that have undergone further tuning, a LFC even more effective than the double suction slot system tested in this research will ultimately be developed.

Declarations

Originality

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Brad A. Gibson

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Nomenclature

Symbols

Greek

- α Velocity disturbance wavenumber, angle of attack
- Γ FDS variable
- Δ FDS variable, incremental change
- δ Boundary layer thickness, FDS variable, incremental change
- δ_w Streamline displacement due to presence of pressure tube close to a wall
- δ^* Boundary layer displacement thickness
- ϵ Apparent shift in probe position
- ε Dielectric coefficient
- η Non-dimensional distance normal to wall
- θ Boundary layer momentum thickness
- Λ Pohlhausen shape factor
- λ Velocity disturbance wavelength
- λ_D Debye length
- μ Dynamic viscosity
- ν Kinematic viscosity
- ξ Suction parameter, arbitrary variable
- ρ Fluid density

- ρ_c Charge number density
- σ Standard deviation
- Φ Discretised velocity disturbance amplitude
- ϕ Velocity disturbance amplitude
- φ Electric potential
- χ Ratio of electrode width to electrode length
- ψ Stream function
- ω Velocity disturbance circular frequency
- $\tilde{\omega}$ FDS variable

Roman

- A FDS variable
- a Plasma breakdown length perpendicular to actuator surface, arbitrary Falkner-Skan variable, arbitrary polynomial coefficient, super-ellipse major radius, local speed of sound
- B FDS variable
- b Plasma breakdown length parallel to actuator surface, arbitrary Falkner-Skan variable, arbitrary polynomial coefficient, electrode spanwise length, super-ellipse minor radius, cavity width
- C Capacitance, FDS variable
- C_p Pressure coefficient
- c Velocity disturbance propagation velocity, arbitrary polynomial coefficient
- $\tilde{c}$ FDS variable
- c_l Airfoil lift coefficient
- D Diode
- d Separation distance between electrodes, pressure tube outside diameter, cavity depth

- E Electric field strength
- E_0 Peak electric field strength, Output voltage of hot wire circuit
- E_b Breakdown electric field strength
- e exponential e
- e_c Electron charge
- err Error
- exp exponential e
- f Body force, applied frequency, measurement frequency, plasma body force, arbitrary Falkner-Skan variable, arbitrary Glauert wall jet variable
- G arbitrary variable
- g Arbitrary Falkner-Skan variable, arbitrary function, acceleration due to gravity
- H Boundary layer shape factor, Investigation height boundary
- h Discretisation distance (y-direction),
- I Length of electrical network (plasma actuator), Gain of current-boosting amplifier (hot wire circuit)
- I_0 Output current of hot wire circuit
- i Squareroot of negative one
- J Number of points in the y-direction
- K Gain of voltage-boosting amplifier (hot wire circuit)
- k_1 Electirc field gradient (x-direction)
- k_2 Electirc field gradient (y-direction)
- k Discretisation distance (x-direction), Trip wire diameter
- k Discretisation distance (x-direction), Trip wire diameter
- L Electrode chordwise length, left-hand side
- ln Natural logarithm

- M Momentum
- m Arbitrary Falkner-Skan variable
- N Maximum number, number of points in the x-direction
- n Number, amplification factor
- P Arbitrary point, static pressure
- q Dynamic pressure
- R Resistance, right-hand side
- Re Reynolds number
- r Variable set (matrix equation)
- $\tilde{r}$ FDS variable
- s Arbitrary variable
- t Time, thickness
- Tu Turbulence intensity
- U Arbitrary variable
- U_∞ Freestream velocity
- u Mean velocity, local x-direction velocity
- V Velocity vector, applied voltage
- v Local y-direction velocity
- v_0 Uniform suction velocity
- w Local z-direction velocity
- x x-direction (chordwise), boundary layer development length, parallel to wall
- y y-direction, normal to wall
- z z-direction (spanwise), height above the Earth's surface

Math

- ∞ Limit at infinity

Subscripts

Greek

- δ Based on boundary layer thickness
- δ^* Based on boundary layer displacement thickness

Roman

- a Pertaining to air, arbitrary resistance
- abs Absolute (error)
- app Applied to actuators
- b Body, pertaining to the backward-going discharge cycle, balance (hot wire bridge)
- $Blasius$ Pertaining to Blasius flow
- C Based on chord length
- c Pertaining to a charge, arbitrary resistance
- $Calculated$ Pertaining to calculated data
- $Cold$ At cold temperatures
- $Control$ Controlled
- $corrected$ Corrected mesurement value
- $crit$ Critical (point of stability)
- d Pertaining to the dielectric, based on pressure tube outside diameter
- e Edge
- $elec$ Pertaining to the electrodes
- $encapsulated$ Pertaining to the encapsulated electrode
- exp Distance to which exposed electrode sits proud above surface
- $exposed$ Pertaining to the exposed electrode
- f Pertaining to the forward-going discharge cycle

- fit Pertaining to a fitted curve
- h Horizontal (x) direction, voltage overshoot
- i Imaginary component, output of CTA bridge, i^{th} element
- $instrument$ Pertaining to the instrument
- j Due to plasma suction
- jet Jet
- k Based on trip wire diameter
- L Based on non-dimensional length item LE Pertaining to the leading edge
- max Maximal
- $measured$ Pertaining to measured data
- N Pertaining to the maximum number N
- n Pertaining to the number n
- Op Operating (hot wire bridge)
- $Published$ Pertaining to published data
- pp Peak-to-Peak
- qi Offset (voltage)
- r Real component
- rel Relative (error)
- S Arbitrary point of interest
- $scatter$ Scatter (measurements)
- $spatial$ Spatial
- t Eddy viscosity
- Tot Total
- tr Transition
- v Pertaining to the vertical (y) direction

- w Due to the wall, hot wire
- x Pertaining to the x-direction
- y Pertaining to the y-direction

Mathematical

- ∞ In the freestream
- 0 At the wall

Superscripts

- $\rightarrow$ Vector quantity
- $'$ Differentiation with respect to the normal direction
- $\acute{}$ Fluctuating quantity
- $\star$ Non-dimensional
- $\dot{}$ Derivative with respect to time

Acronyms

- AC Alternating Current
- CTA Constant Temperature Anemometry
- DBD Dielectric Barrier Discharge
- DC Direct Current
- DE Direct Equation
- DOC Direct Operating Costs
- FDS Finite Differencing Scheme
- FPR Flat Plate Rig
- ID Internal Diameter
- KBM Keller's Box Method
- LFC Laminar Flow Control

- LSA Linear Stability Analysis
- LST Linear Stability Theory
- NRMSD Normalised-Root-Mean-Square-Deviations
- OD Outside (External) Diameter
- OHR Over Heat Ratio
- OSE Orr-Sommerfeld Equation
- PDE Partial Differential Equation
- PDF Portable Document Format
- RSE Rayleigh Stability Equation
- TS Tollmien Schlichting
- ZPG Zero Pressure Gradient