Development and Application of Plasma Actuators for Active Control of High-speed and High Reynolds Number Flows

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Requirements for Actuators in High Reynolds Number and High-speed Flow Control

- Active flow control is often used to manipulate flow instabilities to achieve a desired goal (e.g. prevent separation, enhance mixing, reduce noise, …)
- Instability frequencies normally scale with flow velocity scale and inversely with flow length scale \((U/\ell)\)
- In a laboratory setting for such flow experiments, \(U\) is high, but \(\ell\) is low, resulting in high instability frequency
- In addition, high momentum and high background noise & turbulence in the flow necessitate high amplitude actuation
- Developing a high amplitude and high frequency actuator is a major challenge
- Ironically, these requirements ease up in application (but other issues arise)
Some Applications of Interest

- Jet control for mixing enhancement or noise mitigation
- Shock wave – boundary layer interaction control (e.g. in supersonic inlets)
- Cavity flow control
- Mixing enhancement for combustion (e.g. in scramjet type applications)
High-speed Jet Control for Mixing Enhancement or Noise Suppression

- An axisymmetric jet has **two length scales**, jet diameter \(D\) and initial shear layer momentum thickness \(\theta\), and **three distinct instabilities**
  - **Initial shear layer instability** with a \(St_\theta = f\theta/U\sim 0.01\) to 0.02 (e.g., Michalke 1965; Zaman and Hussain 1981; Ho and Huerre 1984) – \(f\sim 50,000\ Hz\)
  - **Jet preferred mode instability** with a \(St_D = fD/U\sim 0.2\) to 0.6 (e.g., Crow and Champagne 1971; Zaman and Hussain 1980; Ho and Huerre 1984) - \(f\sim 5,000\ Hz\)
  - **Azimuthal mode instability** with a **primary parameter** of \(D/\theta\) (e.g., Michalke 1977; Cohen and Wygnanski 1987; Corke et al. 1991) – **require distributed actuators with individual control**
Initial Shear Layer & Jet Column Instabilities

Forcing Strouhal Number ($St_{DF} = fD/U_j$)

PIV measurements - jet width at half centerline velocity for Mach 0.9 jet ($Re_D = 0.74 \times 10^6$) forced at $m = 0$ using 8 LAFPAs

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Localized Arc Filament Plasma Actuators (LAFPAs)

- A LAFPA constitutes a pair of electrodes (1 mm dia. tungsten) connected to a high voltage (~kV) or a low voltage & transformer power supply.
- We have used 8 actuators with any prescribed frequency, phase, and duty cycle:
  - Frequencies from 0 to 200 kHz
  - With 8 actuators could force azimuthal modes \( m = 0 \) to 3 & ±1, ±2, and ±4
- An actuator provides localized high amplitude heating
  (arc filament cross section is \( \sim 1-2 \text{ mm}^2 \))
Power Supply and Control for Plasma Actuators

DC power supply
1A, 10kV

Switches

Resistors

Capacitor

PCI 8-Channel DAC

8-Ch

Ceramic nozzle extension with 8 actuators

Direct Current Power Supply

Pulse Generator

Controller Switch 1 Capacitor Switch 2

High Voltage Coll

Computer

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Excitation of Azimuthal Modes – 4 of 7

\[ A = A_0 \sin(2\pi f_F t - m\phi) \]

Phase between successive actuation = \( m(360/8) \), \( m=0, 1, 2, \) or 3

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Jet Receptivity & Perturbation Generated by LAFPAs

- Jets are known to be receptive to thermal, aerodynamic, or acoustic perturbations (Moore 1977)
- The most receptive location is just downstream of the nozzle
- LAFPAs impart temperature perturbation (≈300 to 1200°C, depending upon the excitation frequency & duty cycle obtained by spectroscopy – temperature perturbation leads to pressure perturbation

- 2-D Mach 0.9 jet
- Frequency of 20 kHz
- Average temperature of 600°C
- 4 actuators
Experimental Arrangement

- Mach 1.3, 1.65 (conical & contoured) and 2.0 axisymmetric jets
  - 1 inch nozzle exit diameter
  - Reynolds number $1.1 \times 10^6$ to $2.5 \times 10^6$
  - Can be heated to $\sim 1000^\circ F$
- Flow measurements: instantaneous snapshots, ensemble/phase-averaged flow images, PIV measurements, real-time pressure measurements
- Far-field acoustic measurements: both in frequency and time domains

Not to scale

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Phase-averaged Images in Mach 1.3 Axisymmetric Jet Forcing at $St_D = fD/U_j = 0.33$

Baseline jet

Axisymmetric mode ($m=0$)

First helical mode ($m=1$)

Flapping mode ($m=±1$)

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3-D Structure of Phase Averaged Flow: \( m=\pm 1 \) (\( \text{St}_{\text{DF}} \approx 0.3 \)) – Datta Gaitonde (2009)

Rotating view at fixed phase angle

\[
Q = \frac{1}{2} [||\Omega||^2 - ||S||^2]
\]

\( \Omega \) & \( S \): vorticity & rate of strain tensors (Haller, JFM, Vol. 525, 1985)

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Noise Suppression – Mach 0.9 Heated Jet with Temperature Ratio of 2.5

Baseline jet far-field SPL

OASPL for controlled jet with azimuthal mode m = 3

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Shock Wave – Boundary Layer Interaction Control

Touber & Sandham (2009)

DuPont et al. (2008)

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Normalized Streamwise Mean Velocity for Mach 1.9 Flow with $\alpha = 10^\circ$