Exploration of Plasma-Based Flow Control Strategies Using High-Fidelity 3D Simulations

Miguel Visbal
Computational Sciences Branch
Air Vehicles Directorate
Air Force Research Laboratory
Wright-Patterson AFB, OH

Collaborators: D. Rizzetta & D. Gaitonde (AFRL/RBAC)
S. Roy (UFL)

AFOSR DBD Plasma Actuator Workshop
Gainesville, FL - 24 Feb 2010
Simulation Issues

Level of simulation fidelity required for exploration of flow control strategies using DBD actuators

- Reliable “computational experimentation”
- Balanced approach for actuator & fluids – spatio-temporal scales
- Problem is inherently unsteady with broad range of frequencies
  - primary frequency generates fine-scale turbulence
  - modulating frequencies (duty cycle) interacts with large-scale coherent structures
- Physics-based or phenomenological reduced order models
- Loosely-coupled (one-way interaction)
- Fully-coupled
- 2D versus 3D models
- DNS, LES, RANS methodologies

What we need:
- Spatio-temporal distribution of volume forces from experiments or high-fidelity plasma simulations
- Near-field velocity measurements for model calibration
Control Strategies

- High-fidelity simulation critical for effective flow control strategies
  - actuator size and aspect ratio
  - actuator orientation
  - multiple actuator arrangement
  - 3D actuators
  - tailor actuator design to specific flow effects

- Examine critical role of unsteady forcing versus momentum injection mechanisms

- Compare phenomenological and first-principles modeling approaches

- Control of laminar versus turbulent flows
  - boundary-layer laminar-turbulent transition effects
Large-Eddy Simulation of Separation Control

\[ \text{Re}_c = 9.36 \times 10^5 \quad \text{M}_\infty = 0.1 \]

NASA/AFOSR CFD Validation Workshop Turbulent Separation Control

**U-velocity**

**Reynolds stress**

**ZNMF oscillatory jet**

**Phase-averaged vorticity**

*LES* techniques capture effectiveness of active flow control not attainable with standard *URANS* approaches
**Governing Equations**

### 3-D Navier-Stokes

\[
\frac{\partial \rho^*}{\partial t^*} + \nabla^* \cdot \left( \rho^* \vec{U}^* \right) = 0
\]

\[
\frac{\partial \rho^* \vec{U}^*}{\partial t^*} + \nabla^* \cdot \left[ \rho^* \vec{U}^* \vec{U}^* + \rho^* \vec{I}^* \right] - \frac{1}{Re} \nabla^* \cdot \vec{r}^* - D_{c_q} \vec{E}^* = D_{c_q} \vec{U}^* \cdot \vec{E}
\]

\[
\frac{\partial \rho^* \vec{e}^*}{\partial t^*} + \nabla^* \cdot \left[ (\rho^* \vec{e} + p^*) \vec{U}^* \right] - \frac{1}{Re} \left( \vec{U}^* \cdot \vec{r}^* \right) - \frac{1}{(\gamma - 1) \Pr M^2 Re Q_{ht}^*} = D_{c_q} \vec{U}^* \cdot \vec{E}
\]

Force is specified through charge and electric field product:

- **Phenomenological models**
  - Shyy et al. (2002)
  - Gaitonde, Visbal & Roy (2005)
- **Loosely-coupled first-principles model**

**Computational Approach:** *FDL3DI Solver*

- 6th-order compact scheme
- 8th-order low-pass filter for regularization at non-resolved wavenumbers (ILES)

**Average force**

\[ D_c = \frac{\rho_{c, ref} \vec{e} \vec{E} \vec{L}_{ref}}{\rho_{ref} U_{ref}^2} \]
Considerations Regarding Actuator Applications

orientation

Amplitude modulation

\[ F = A(\tau) F_0 \]

\[ S_\text{tp} = f_p L/U \]

duty = \( T_d / T_p \)

DBD as a tripping device

- u-velocity
- vorticity magnitude
Unsteady flow structure in actuator near field

St=1.0

St=0.25 Vortex dipole

Roy & Wang
Control of Wing Stall Using DBD Actuators: Momentum injection vs. unsteady forcing

co-flow steady
co-flow pulsed
counter-flow pulsed

surface pressure

u-profile, x/c = 0.42
Effect of Pulsing Frequency

$St_p = 1.0$

$St_p = 8.0$

surface pressure

$-C_p$

baseline
$St_p = 1.0$
$St_p = 2.0$
$St_p = 4.0$
$St_p = 8.0$

$x/c$
Control of Laminar vs. Turbulent Separation

- **Baseline**
- **Pulsed Co-Flow Actuator, D_c = 150, F^+ ~ 7.0**
- **Counter-Flow Actuator, D_c = 25.0**

- L_{sep} / c = 2.2
- L_{sep} / c = 1.65
- F^+ ~ 4.4
isolated actuator in ambient air used to optimize model free parameters

Experiments:
Schatzman & Thomas (2008)
High-fidelity simulation is critical to exploration of flow control strategies using DBD actuators - provide qualitative trends - understanding of actuation effectiveness - may identify future actuator designs goals.

Transition/turbulence enhancement is main control mechanism due receptivity of the flow to unsteady forcing.

A counter-flow actuator provides an effective on-demand boundary-layer tripping device found to be effective for laminar separation control (e.g. low-pressure turbines, low Re wings).

For turbulent separation, actuator input must exceed a certain threshold which has implications for scaling to higher velocities.

Need spatio-temporal characterization of forces for model implementation derived from experiments and/or detailed plasma simulations.

Alternatively, near field 3D flow field measurements would be useful for model calibration in a loosely-coupled approach.
Potential areas of continued exploration:

- Cross-flow instability on swept wings using distributed plasma actuators
- Micro-air-vehicles (gust, propulsion, how to control transition at low Reynolds numbers, 3D actuators)
- Aero-optics (high frequency actuation for suppression of aberrating scales, no injection of fluid with disparate index of refraction)
- Aerodynamics/ Aero-acoustics of wind turbines
- Aero-elastic mitigation