Design and Evaluation of Enhanced Dielectric-Barrier-Discharge Actuators

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Dielectric Barrier Discharge Actuator

Non-thermal, non-equilibrium plasma

Typical Dielectric Barrier Discharge on Glass
\[ f = 5 \text{ kHz} \]
Outline

• Relevance to NASA Aeronautics
• Description of effort’s scope and rationale
• Experimental effort (dielectric and DBD force data)
• Alternative 1-D volume discharges
• Conclusions
Can DBD Actuators Support High Reynolds Number Flight Flow Control?

- While electronic DBD flow control is currently a relatively weak effect, its robustness, controllability and simplicity could make it valuable option for future generations of aircraft.

- In order to fulfill that vision, pursuit of new innovations and understanding physical mechanisms must proceed.
Leveraging Activities

– NASA Aeronautics Research Institute (NARI) Seedling Award
  • NARI seeks and develops new and promising aeronautics ideas for transfer to mainline project funding.
  • Current Goal: Explore materials of varying microstructure and chemistry, particularly aerogels/nanofoams, for enhanced performance of DBD flow control actuators.

– NATO STO/CSO AVT-190 – “Plasma Based Flow Control for Performance and Control of Military Vehicles”
  • Goal: Provide DBD code validation data (thrust, velocity) agreed upon by multiple NATO and PfP (Partners for Peace) participants.
Dielectric Terminology

Poisson’s equation drives DBD electrostatic forces

\[
\nabla \cdot \vec{D} = \rho_c
\]

Definition of displacement field

\[
\vec{D} = \varepsilon_o \vec{E} + \vec{P} = \varepsilon_o \varepsilon_r \vec{E}
\]

P = polarization field
D = displacement field
E = electric field
\varepsilon_0 =\text{ permittivity of free space}
\varepsilon_r =\text{ relative permittivity of material}
\rho_c =\text{charge density}
Force Enhancement with Low Permittivity Dielectrics

Adapted from:
Thomas F., et. al., AIAA J., 2009 and

Aerogel Supports DBD Plasma

*https://technology.grc.nasa.gov/featured-tech/aerogels.shtm
Force Enhancement with Surface Coatings

This may be a humidity effect and not a catalytic phenomena

Titanium Oxide: Photocatalyst and Wide Band-Gap Semiconductor

From: Fine and Brickner, AIAA J., No. 12, Dec 2010
Guiding Questions

• Are some materials superior to others in their ability to mediate creation of DBD body force?

• What is the role of microstructure and chemical composition?

• How do volume and surface properties affect performance?
  • Permittivity and dissipation
  • Secondary electron emission (SEE)
  • Catalytic/photocatalytic effects
  • Surface conductivity and chemical coatings
    – Surfactants (anionic, cationic, non-ionic)
    – Antioxidants (radical scavenger)
    – Adsorbed moisture (relative humidity)
1. Characterize a variety of existing dielectric materials seeking to explain differences in body force generation using:
   - Dielectric properties
   - Reaction force
   - Electrical charge transfer
   - Lumped-parameter 1-D circuit simulations

2. Use this information to develop new materials optimized for DBD applications
Equipment for Materials Characterization

Dielectric Constant and Loss Tangent

Dielectric Breakdown Strength
Measured Dielectric Constant for Various Materials

Desired properties: Low dielectric constant and loss
Measured Dielectric Constant for Various Materials

- Frequency [Hz]
- Dielectric Constant
- Tan [δ]

Materials:
- MicroFoam
- PTFE
- LEXAN
- PMMA
- ULTEM
- PEEK
- Themalux
- Upilex
- Kapton
- Glass
DBD Thrust Measurement Equipment

FPCB DBD Thrust Stand

Typical DBD Model

Original Thrust Stand, USAFA, 2005
Error Due to Electrostatic Induction Between Model and Surroundings

- Model with charge $Q_M$ is in electrostatic force equilibrium with surroundings.
- Uncontrolled physical or electrical (charge) changes may lead to measurement error.
- Humidity in the enclosure has a large, first order effect on DBD force.

Force balance and shield grounded
Effect of Relative Humidity: Clean Glass Substrate

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>rh=69%</th>
<th>rh=0%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust (mN/m)</td>
<td></td>
<td></td>
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</tbody>
</table>

Zero shifts due to charge build-up
Thrust Data for Dielectric Materials

Materials (t: mm, $\varepsilon_r$)

- PEEK (3.1, 3.2)
- Ultem (3.2, 3.0)
- Lexan (2.3, 2.7)
- Acrylic (2.0, 3.2)
- Glass (1.2, 7.8)
- Teflon (3.3, 2.1)
- Boron Nitride (7.3, 4.0)
- Aerogel (0.5, 1.1)
Thrust Data for Dielectric Materials

Thrust \( (\text{mN/m}) \) vs. Applied \( V \) (volt pp)

Materials (t: mm, \( \varepsilon_r \))
- PEEK (3.1, 3.2)
- Ultem (3.2, 3.0)
- Lexan (2.3, 2.7)
- Acrylic (2.0, 3.2)
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\( T \propto V^{3.5} \)

Filamentary region (higher V supply required) \( T \propto V^{2.3} \)

Thrust all lin 2
1D Volume Discharge May Offer Advantages for Dielectric Testing

Volume Discharge (One-dimensional)  
Surface Discharge (Two-dimensional)
One Dimensional Volume Discharge Apparatus

Variable gap volume discharge tester

Typical DBD volume discharge
Typical 1-D Cyclogram

Acrylic, thickness=0.94 mm, er=3.2, f=1 kHz

Cyclogram slopes are proportional to capacitance

Q/C_p (volt)

Applied Voltage (kV)
Cyclogram Characteristics for different materials

![Graph showing Q/Cp vs Vs (kV) for different materials]

- **ACRYLIC**
- **ULTEM**
- **TEFLON**
- **AEROGEL**
Parametric Analysis of Cyclogram Characteristics (frequency, voltage, gap, thickness, permittivity)

Teflon
f=1000 Hz

thickness (mm)
0.25
0.38
0.51
0.79
1.04

Vp (volt)

Vs (kV)
One Dimensional Circuit Simulation of the Actuator Material and Test Environment*

*Data fitting using Qucsator (0.0.18) and SageMath (5.12)
Summary / Conclusions

• Goal 1: Characterize existing dielectric materials seeking to explain differences in body force generation.
  – Implemented dielectric and force diagnostics, surface coatings, circuit simulations and 1D charge transfer technique.
  – Studied a dielectric properties and performance of a variety of organic and inorganic materials.
  – Demonstrated that polyimide aerogels can support a DBD plasma.
  – Measurement uncertainties due to inadequately controlled system electrostatics and variable atmospheric humidity preclude conclusive material assessments at this time.
• Goal 2: Use this information to develop new materials optimized for DBD applications.

  • Refined diagnostics with increased resolution and accuracy are required to differentiate DBD responses due solely to bulk permittivity and geometry from those due to possible plasma/surface (material) interaction effects.

  • Higher voltage power supply ( > 20kV pp) is required to examine force saturation effects where surface interactions are more likely to be manifest.
Future Directions

• Continue fundamental physics research of DBD dielectric materials.

• Identify specific flow features amenable to active DBD flow control and align DBD research with aeronautical applications

• Provide estimates of the impact of DBD forcing on airplane system energy resources.

• Identify appropriate program(s) within ARMD best suited for DBD research and other related direct, ionized gas flow control concepts (plasma arcs, spark jets, etc.)
And if all else fails: Consider **DBD Art and Music**!

Copper foil on 1.2 mm thick glass

- \( V = 20 \text{ kVpp} @ 1 \text{ kHz} \)
- **Nikkor 50mm f/1.4**, 1/5 sec exp.

Tone scale (\( C_6 \))

- \( V = 20 \text{ kVpp} \)
- \( 1046.5 < f < 2093.0 \)

Concept: Ken Miller, Eagle Harbor Technologies, Seattle, WA
END