Rotational Testbed for Coulomb Induced Spacecraft Attitude Control

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Outline

• Coulomb Charge Control
• Remote Coulomb De-spin
• Electrostatic Modeling
• Experimental Setup
• Modeling Disturbances
• Passive Charging
• Spin-up & De-spin Results
• Conclusion / Questions
Coulomb charge control

- Research effort initiated a decade ago, to charge spacecraft in close proximity for relative position control
- Two 5 m diameter spacecraft separated by 20 m, charged to ±30 kV, exert 2 mN force
- Debye shielding effect
  - inhibits electric fields in LEO but manageable in HEO
- Applications
  - Formation flying (separated spacecraft interferometry)
  - Electrostatic tugs (touchless re-orbiting of debris objects)
Remote Coulomb De-spin

- Charged non-spherical conductors experience torques & off-axis forces
- Remove rotation rate from non-cooperative spacecraft before rendezvous (to < 1 deg/s)
- Motivation: orbital debris removal at GEO
  - Docked satellite tug
  - Satellite servicing missions
Electrostatic Modeling

Multi-Sphere Method (MSM)

- MSM Surface Population
- MSM Volume Population
- Effective Sphere
- Point Charge
- Finite Element Analysis

Accuracy vs Computation Time
Electrostatic Modeling

Multi-Sphere Method (MSM)

$\phi_i = k_c \frac{q_i}{R_i} + \sum_{j=1, j \neq i}^{m} k_c \frac{q_j}{r_{i,j}}$

Accuracy

Computation Time

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Electrostatic Modeling

Simple 3x1 cylinder, representative of Centaur upper stage rocket

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{cyl}$</td>
<td>182.1</td>
<td>g</td>
<td>Cylinder mass</td>
</tr>
<tr>
<td>$I_{cyl}$</td>
<td>3.30</td>
<td>g·m²</td>
<td>Moment of inertia</td>
</tr>
<tr>
<td>$l$</td>
<td>45</td>
<td>cm</td>
<td>Separation</td>
</tr>
<tr>
<td>$d$</td>
<td>17.353</td>
<td>cm</td>
<td>MSM Parameters</td>
</tr>
<tr>
<td>$R_a, R_c$</td>
<td>8.8634</td>
<td>cm</td>
<td>MSM Parameters</td>
</tr>
<tr>
<td>$R_b$</td>
<td>9.7664</td>
<td>cm</td>
<td>MSM Parameters</td>
</tr>
</tbody>
</table>

\[
\begin{bmatrix}
\phi_1 \\
\phi_2 \\
\phi_2 \\
\phi_2
\end{bmatrix} = k_c \begin{bmatrix}
1/R_1 & 1/r_a & 1/r_b & 1/r_c \\
1/r_a & 1/R_2,a & 1/l & 1/2l \\
1/r_b & 1/l & 1/R_2,b & 1/l \\
1/r_c & 1/2l & 1/l & 1/R_2,c
\end{bmatrix} \begin{bmatrix}
q_1 \\
q_a \\
q_b \\
q_c
\end{bmatrix}
\]

\[
M_2 = k_c q_1(d, \theta) l d \sin \theta \left( \frac{q_c(d, \theta)}{r_c^3(d, \theta)} - \frac{q_a(d, \theta)}{r_a^3(d, \theta)} \right)
\]
Experimental Setup

1. Laser distance sensor
2. Custom disc with varying length radius
3. Ceramic bearing
4. DAQ system
5. High voltage power supply

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Simulation runs in MATLAB (ode45)

1. Bearing Friction
   \[ M_B = \gamma F_a \]

2. Atmospheric Drag
   \[ M_D = \frac{\rho \omega^2 C_d D L^4}{64} \]

* Equivalent at: 38 deg/s
Passive charging

1. Modify MSM to capture constant charge, not constant potential

\[
\begin{bmatrix}
\phi_1/k_c \\
0 \\
0 \\
q_2
\end{bmatrix}
= 
\begin{bmatrix}
1/R_1 & 1/r_a & 1/r_b & 1/r_c & 0 \\
1/r_a & 1/R_{2,a} & 1/l & 1/2l & -1 \\
1/r_b & 1/l & 1/R_{2,b} & 1/l & -1 \\
1/r_c & 1/2l & 1/l & 1/R_{2,c} & -1 \\
0 & 1 & 1 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
q_1 \\
q_a \\
q_b \\
q_c \\
\phi_2/k_c
\end{bmatrix}
\]

2. Characterize charge drain due to interaction with atmospheric environment and bearing mount
   - Low capacitance makes voltage measurement difficult
   - Use surface DC voltmeter measurements
Passive charging

(a) Charge drain, various configurations

- Par., $V_{spk} = 0 \text{ kV}$
- Par., $V_{spk} = -15 \text{ kV}$
- Par., $V_{spk} = +15 \text{ kV}$
- Perp., $V_{spk} = 0 \text{ kV}$
- Perp., $V_{spk} = -15 \text{ kV}$
- Perp., $V_{spk} = +15 \text{ kV}$

(b) Charge drain, curve fit

$V(t) = V_0[0.87 - 0.00041t + 0.127e^{-0.017t}]$
Remote cylinder rotation control by Coulomb charging
Spin up to rate where Coulomb torques balance with disturbances

<table>
<thead>
<tr>
<th>Condition</th>
<th>Spin-up Control Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^\circ + \theta_{DB} &lt; \theta &lt; 90^\circ - \theta_{DB}$</td>
<td>$\phi_1 = -30 \text{ kV}$</td>
</tr>
<tr>
<td>$180^\circ + \theta_{DB} &lt; \theta &lt; 270^\circ - \theta_{DB}$</td>
<td>$\phi_1 = +30 \text{ kV}$</td>
</tr>
<tr>
<td>$90^\circ + \theta_{DB} &lt; \theta &lt; 180^\circ - \theta_{DB}$</td>
<td>$\phi_1 = +30 \text{ kV}$</td>
</tr>
<tr>
<td>$270^\circ + \theta_{DB} &lt; \theta &lt; 360^\circ - \theta_{DB}$</td>
<td>$\phi_1 = -30 \text{ kV}$</td>
</tr>
</tbody>
</table>

(a) Angular velocity

Simulation
Experimental

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Spin-up Control Results

Spin up to rate where Coulomb torques balance with disturbances.

\[
\begin{array}{|c|c|c|}
\hline
\text{CCW (}\omega > 0\text{)} & \phi_1 = -30 \text{ kV} & \phi_1 = +30 \text{ kV} \\
\text{CW (}\omega < 0\text{)} & \phi_1 = +30 \text{ kV} & \phi_1 = -30 \text{ kV} \\
\hline
\end{array}
\]

(b) Simulated electric potentials
Spin-up Control Results

Spin up to rate where Coulomb torques balance with disturbances

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<th>Torque</th>
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<tbody>
<tr>
<td>CCW ($\omega &gt; 0$)</td>
<td>$\phi_1 = -30 \text{ kV}$</td>
</tr>
<tr>
<td>CW ($\omega &lt; 0$)</td>
<td>$\phi_1 = +30 \text{ kV}$</td>
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</tbody>
</table>

(c) Simulated torques

$M \ [\text{mN.m}]$

Time $[\text{s}]$

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De-spin Control Results

- Opposite control to arrest rotation rate of cylinder
- Cylinder rotation arrested 3 times faster than natural de-spin from disturbances
- Verification of remote Coulomb de-spin concept
Conclusion

- Rotational actuation by Coulomb torques verified by terrestrial testbed
- Disturbances successfully characterized and numerical models match experimental results extremely well
- De-spin concept validated for cylindrical conductor
- Hardware limitations identified, improve fidelity in future testbed iterations to allow for more accurate validation of attitude control algorithms
  - Disturbance torques are smaller but same order of magnitude as maximum attainable Coulomb torques
  - Accuracy of rotational encoding (2 Hz noise with 1σ amplitude of 2 deg)
  - Polarity switching lag of HVPS (up to 1 sec) limits torques at high rotation rates
- Ultimate goal is to move experiments to vacuum environment
Acknowledgement
This material is based upon work supported by: NASA Science & Technology Research Fellowship (NASA Grant #NNX11AN47H).