Preliminary Measurements of the Motion of Arcjet Current Channel Using Inductive Magnetic Probes

Magnus A. Haw
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NASA Ames Aerodynamic Heating Facility (AHF)

- Arcjet facility for testing materials in high enthalpy flows
- Critical infrastructure for certifying heatshields for flight
10 MW heater geometry

- Tungsten Cathode
- Cooling Water Passage
- Gas Injection Port
- Copper Anode
- Throat
- Nozzle
Arcjet Facility Challenges

Flight Condition Matching
- Higher mach number
- Higher enthalpy
- Gas mixture
- Radiative shock heating
- Larger test models

Testing Fidelity
- Facility reproducibility
- Uncertainty quantification
- Diagnostic development
Arcjet Heater Simulator (ARChES)

- Compressible flow
- Magnetic fields
- Electric current
- Coupled Thermo
- 3D Radiation

Applications

- Physics based inputs for nozzle flow CFD
- Independent verification and validation of existing diagnostics/simulations
- NextGen arcjet design
- Facility maintenance
- Facility reproducibility
Magnetic Kink Instability

- Magnetic instability of current channels
- Radial perturbations are unstable to growth
Magnetic measurements on AHF constrictor

Questions addressed
- Is the kink instability present in the arcjet heater column?
- If so, what are the parameters of the fluctuations?

Diagnostics
- Inductive magnetic probes

Relevance
- Electrode wear patterns
- Facility reproducibility
- Gas mixing
Diagnostic Design

Design of multiple probe iterations and optical link circuit
Inductive magnetic probes

Increasing B-field

Pros
1. Sensitive to fast changes in B-field
2. Design is simple and easily modified

Cons
1. Measurement is not absolute
2. Integration errors limit measurement time to short intervals (< 50 ms)

Voltage proportional to time derivative of B

\[ V_{emf} = -N A \frac{\partial B}{\partial t} \]
Measuring arcjet kink instability

- Coils can be customized for arcjet geometry
- Measurements can be taken outside the arc column
- Large signal to noise: \( \frac{\text{dB}}{\text{dt}} \sim \frac{T}{s} \)
Optimizing Inductive Probes

Probe self-attenuation:

\[ \frac{1}{\sqrt{1 + (\omega L_p / R_L)^2}} \]

For a typical coil with \( L_p = N^2 L_0 \), the optimal number of turns is,

\[ N_{\text{best}} = \frac{R_L}{\omega L_0} \]

So \( N \sim [50, 300] \) for the arcjet context
3D Printed Mounts for Fast Prototyping

6 x 4.2 x 1 cm, N = 50

4.2 x 2.4 x 0.8 cm, N = 100
Optical Link

- Provides electrical isolation (safety req.)
- Reduces electrical noise/pickup from long cables
Optical Link Transmitter

- Current amplifier circuit feeding high power IR LED (820 nm)
- Robust linear circuit
- Transistor amplification varies, careful calibration required
Optical Link Receiver

- Reverse biased IR photodiode (820 nm)
- Matched pair with transmitter, sensitive up to 125 MHz
Optical Link Specs

Optical Link Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Linear range [V]</td>
<td>(-3.17, 1.8)</td>
</tr>
<tr>
<td>Frequency range [MHz]</td>
<td>(0, 10)</td>
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<tr>
<td>Transmission range [km]</td>
<td>2.7</td>
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<tr>
<td>Dimensions [mm]</td>
<td>100x85x20</td>
</tr>
<tr>
<td>Cost/channel</td>
<td>$50</td>
</tr>
</tbody>
</table>
Calibration of Sensors + Optical Links

- Helmholtz coils are used for calibration of the sensor + optical link system.
- Coils are calibrated with a specific optical link channel.
Magnetic Measurements on AHF

Single and differential measurements of AHF magnetic field
Single Coil Measurements
Single Coil Measurements

Arcjet B-field

Arcjet B-field Spectrum

360 Hz
Power supply oscillates at +8 Amps @360 Hz

These oscillations obscure any signal from motion of the current channel

The contribution from the power supply must be subtracted out to measure the current channel motion

Single Coil Measurements
Differential dB/dt Measurements

\[ B_1 = \frac{\mu_0(I_0 + \partial I)}{2\pi(R - \delta)} + \partial B \]

\[ B_2 = \frac{\mu_0(I_0 + \partial I)}{2\pi(R + \delta)} + \partial B \]

\[ \Delta B = B_1 - B_2 \]

- Direct measurement of motion
- Subtracts out common noise
- Subtracts out power supply fluctuations
Probe Placement for Differential Measurements
5 ms dB/dt data taken at 1 MHz sampling rate

Calibration of channels is sufficiently accurate to subtract out noise

Differential signal observed
Integration of Bdot measurements over 5 ms

ΔB present at low and high frequencies
Inferring Current Channel Position

Coil B-field

\[ \bar{B} = \frac{1}{r_2 - r_1} \int_{r_1}^{r_2} \frac{\mu_0 I}{2\pi r} \, dr = \frac{\mu_0 I}{2\pi(r_2 - r_1)} \ln \left( \frac{r_2}{r_1} \right) \]

Differential B-field

\[ \Delta \bar{B} = \bar{B}_b - \bar{B}_a = \frac{\mu_0 I}{2\pi(r_2 - r_1)} \left[ \ln \left( \frac{r_2 - \delta}{r_1 - \delta} \right) - \ln \left( \frac{r_2 + \delta}{r_1 + \delta} \right) \right] \]

Displacement from axis

\[ \delta = \frac{\sqrt{4r_1 r_2 \chi^2 + (r_2 - r_1)^2(\chi + 2)^2} - (r_2 - r_1)(\chi + 2)}{2\chi}, \text{ where } \chi = \exp \left( \frac{2\pi \Delta B(r_2 - r_1)}{\mu_0 I} \right) - 1 \]
4mm displacements observed at ~700 Hz

2mm displacements observed at ~2 kHz

δ ~ 13% of heater radius
Discussion

- Current channel corresponds to enthalpy profile (path of least $\Omega$)
- Motion of current channel implies equivalent motion of enthalpy profile

Affects interpretation of

- Time averaged heat flux measurements
- Time averaged spectral measurements
- Inferred spatial enthalpy profile
Future Work

Questions addressed:

- Does the current attach at one location on a given electrode?
- Does this attachment point rotate and with what frequency?
- Does the current detach?

Diagnostics

- Bdot sensors
- Hall sensors

Relevance

- Electrode wear/damage
- Higher power electrode development

3-axis Hall sensor development
ARCHeS simulations predicted kink instability.

Magnetic sensors were developed to measure this phenomenon.

Measurements indicate ~4mm displacements at kHz freq.
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Any Questions?