Atmospheric Turbulence Measurements Using Small Unmanned Aircraft Systems

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Small UAS in Rugged Terrain

- Sagebrush/dirt in Utah
- Arroyo dust/rocks in Peru
- Dense forests/rain in Japan
- North Shore Alaska tundra/snow
Turbulence Measurement on Small UAS

Requires high-bandwidth measurements to obtain confident spectral estimates (wide frequency range for spectral fits)

Requires small sensor elements for a small thermal time constant (e.g. micron-diameter wires for temperature, velocity)

Sensor elements must be protected from harsh operational conditions, without corrupting the turbulence measurements
DataHawk Fine Wire Turbulence Sensor

- 5 µm dia. Pt wires
- Custom electronics
  - 400 Hz wire bandwidth (CVA)
  - 800 Hz sampling
  - Auto zero
  - Ambient temperature compensation
- 20g, 0.5W, $500

DataHawk
- 1.3m span, 1.3 kg
- 10-20 m/s
- 100 min duration
Fine-Wire Convective Heat Transfer Model

**Convective Flow**

\[ V \sim 10 \text{ m/s} \]

- **Wire Diameter**
  \[ d = 5 \mu m \]

Air Properties:

- Thermal Conductivity \( k \)
- Kinematic Viscosity \( \nu \)

**Wire Length**

\[ L = 2 \text{ mm} \]

- End effects ignored \( (L/d = 400) \)

- Electric current through wire cross section produces Joule heating power \( P \) and resultant wire temperature \( T_w \) according to

\[
I \, V = P = H(V)(T_w - T_a)
\]

\[
Nu = \frac{h \, d}{k} \quad Re = \frac{V \, d}{\nu}
\]

\[
P = Nu(Re) \pi k L \, (T_w - T_a)
\]

Radiative heat transfer ignored (< 1%)
Environmental Turbulence Power Spectra

Heisenberg Turbulence Model

Turbulence Parameter:
- Kinetic Energy
  \[ E = \frac{\varepsilon}{N^3} \]
- Dissipation Rate \( \varepsilon \)

- Ozmidov Scale
  \[ L_0 = \left( \frac{\varepsilon}{N^3} \right)^{1/2} \]
- Kolmogorov Scale
  \[ L_K = \left( \frac{\nu^3}{\varepsilon} \right)^{1/4} \]
- Quantization noise floor

- Ozmidov Outer Scale Limit
  \[ (N = 0.0215 \text{ s}^{-1}) \]
- Inertial Cascade
- Viscous Knee
- Sampling Nyquist Rate
- Quantum noise floor
- Electronics Noise Floor

**frequency = velocity/scale**
Turbulence Spectral Estimation

Two different 5 sec time records of relative wind, detrended and windowed

\[ PSD_V = \alpha f^{-5/3} \]
\[ \varepsilon = c a^{3/2} / U \]

*Frehlich et al 2003*
Sensor Protection Schemes

• Mounting behind the airframe leading edge
• Protective cylindrical shroud with ball deflector: protects against
  ▪ Handling, flight ops
  ▪ Solar radiation
  ▪ Debris, raindrops and snowflakes
  ▪ Cylindrical shroud only
    ▪ Avoids variable ball wake
    ▪ Highly robust, except for particles entering the throat
  ▪ Wires mounted “backwards” (shielded by their own prongs)
DH Turbulence sensors
Obstructive Effects

- DataHawk airframe
- Protective shroud
- Upstream wire and its prongs
- Leading edge of the sensor board
Wind Tunnel Sensor Characterization

- Test section 3m long, 0.8m square
- Nominal free stream velocity: 15m/s
- Traverse strut equipped with sensor mounting platform
- Coldwire, Hotwire and Pitot differential pressure sensors
- Upstream turbulence-generating grid

Turbulent Flow Field

- 9 bars produce $Re = 25400^*$
- ~15 degree wake spread angle $^*$
- Local velocity fluctuations less than 10% of the mean free stream velocity $^*$
- Outer scale of turbulence at about 30 Hz (0.5m) $^*$

*$Schlichting – BLT$
*$Gutkin et al 2016$
*$Parnaudeau et al 2008$
• Free stream measurement avoids wake effects
• Characteristic $f^{-5/3}$ spectral slope from 30 Hz to 400 Hz
Sensor in normal configuration

- Hotwire and coldwire prongs facing down stream
- Slope is reduced from the expected $f^{-5/3}$ inertial cascade slope
- The obstruction increases turbulent intensity at small scales (but much larger than the expected millimeter scales)
Effect of 3-wire board leading edge

- Isolate the effect of wake due to leading edge
- Shroud extends beyond 3-wire board leading edge
- Extension length – 0.63 cm
- Suppressed power above 20Hz
- The current design uses the extended shroud
Effect of Prongs

- Extended HW prongs
- Avoid leading edge effects
- Elevation in power expected at high frequencies only (small scale)
- The obstruction effect extends to lower scales also
- Prongs elevate the turbulence
Effect of Shroud diameter

- Shroud Diameter increased to 3 cm
- Shroud extends leading edge by 0.63 cm
- HW and CW facing upstream
- Elevated HW and CW prongs separated by an angle (forming a ‘V’)

![Diagram showing shroud configurations with labels for Hotwire, Coldwire, Extended shroud, Large shroud - Flared, and dimensions for 1 cm and 3 cm.}
Effect of Shroud diameter

- Comparing extended shroud with small and large diameter
  - Average power in smaller shroud is slightly less
  - Easy to change the wires in case of breakage
- Flaring the shroud has no noticeable effect
Effect of DH airframe

- Flight test with simultaneous measurements in the free atmosphere
- Sensors separation distance – 0.3m
Free Atmosphere Characterization on DataHawk

- 80 spectral estimates (using 5 s time records)
- Both low and high turbulence conditions
- Mean PSD intensity reduction from FS to protected measurements = 8 %
- $\varepsilon$ reduction factor 0.89 was obtained
- FS mount accentuates vibration artifacts (> 50 Hz)

![Graph showing usable spectral content, HF noise, and motor vibrations with 5/3 slope line.]
Conclusion

- The protective schemes employed affect 0.5m scales and smaller
  - Shroud
  - Prongs
  - DataHawk body
- But these effects are predicted to affect millimeter scales only
- The study shows the effects extends to much larger scales than predicted