Electric Motor Noise from Small Quadcopters: Part II – Source Characteristics

Brenda Henderson
Dennis Huff
Jordan Cluts
Charles Ruggeri
NASA Glenn Research Center

AIAA/CEAS Aeroacoustics Conference
Atlanta, GA
25 – 29 June 2018
Objectives of Study

• Determine impact of motor type, controller type, loading and vehicle installation on acoustic radiation

• Investigate elements of a noise prediction approach for future use with NASA’s Aircraft Noise Prediction Program (ANOPP)
Electric Motor Noise Theory

Pressure from Magnetic Field

- Radial force in terms of radial pressure
  \[ F_R(\alpha, t) = \int p_R dA \]

- Radial pressure is obtained from Maxwell’s stress tensor
  \[ p_R(\alpha, t) = \frac{1}{2\mu_o} \left[ b_R^2(\alpha, t) - b_T^2(\alpha, t) \right] \]

  - \( b = \) magnetic flux density
  - \( \mu_o = \) magnetic permeability = constant

  - \( b_T \ll b_R \)

  - \( b_R = b_{Rpm} + b_{RS} \)

- Resulting radial pressure on outer surface (rotor in this case)
  \[ p_R(\alpha, t) \approx \frac{1}{2\mu_o} \left[ b_{Rpm}^2(\alpha, t) + 2b_{Rpm}(\alpha, t)b_{RS} + b_{RS}^2(\alpha, t) \right] \]

\[ f \propto nf_{motor} \propto mf_l \]

\[ f_l = f_{motor} / \#pole \ pairs \ (N) \]

Dynamic rotor eccentricity \( \pm qf_l/N \)
Electric Motor Noise Theory (con’t)

Pressure from Magnetic Field

• Field associated with permanent magnets \( (b_{Rpm}) \)
  – Geometry (out-running/in-running, radius, gap distance, # poles, etc.)
  – Magnet properties

• Field associated with Stator \( (b_{Rs}) \)
  – Geometry (radius, gap distance, # slots, slot opening, etc.)
  – Winding scheme (winding distribution factor, turns/phase, coil span, etc.)
  – Load (current)
Electric Motor Noise Theory (con’t)

Structural Vibration

• Analytical Techniques
  – Thick shell
  – Thin shell
  – Stringers
  – Rotational effects
  – Stator equations

• Finite Element Analysis
Electric Motor Noise Theory (con’t)

Acoustic Radiation

• Approaches
  – Infinite cylinder
  – Finite cylinder with rigid baffles
  – Simplified numerical calculation

• On acoustic boundary
  – Frequency
    ➢ Only need to predict radiation in relevant frequency bands
    ➢ Relevant frequency bands depend on structural response and noise perception
  – Displacement for relevant modes
Acoustic Testing Laboratory (ATL)

- Small Array
- Medium Array
- Motor
- Large Array
Configurations and Conditions

**Motors**

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Type</th>
<th>$K_v$</th>
<th>L/D</th>
</tr>
</thead>
<tbody>
<tr>
<td>DJI</td>
<td>2212</td>
<td>920</td>
<td>0.49</td>
</tr>
<tr>
<td>DJI</td>
<td>2312</td>
<td>960</td>
<td>0.49</td>
</tr>
<tr>
<td>3DR</td>
<td>2830</td>
<td>850</td>
<td>0.54</td>
</tr>
</tbody>
</table>

Stator Diameter (mm): 2212
Stator Length (mm): 2830

Out-Runner, **BLDC Motors**
14 Poles, 12 Slots
Delta dLRK or LRK Windings

$K_v \propto \frac{1}{K_T} = f(x(# \text{ conductors}))$

# conductors $\uparrow K_v$ $\downarrow$

**Controllers**

<table>
<thead>
<tr>
<th>Controller Type</th>
<th>Manufacturer</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>3DR</td>
<td></td>
</tr>
<tr>
<td>Conventional</td>
<td>DJI</td>
<td>E300</td>
</tr>
<tr>
<td>Sine Wave</td>
<td>DJI</td>
<td>420S</td>
</tr>
</tbody>
</table>

**Conditions**

<table>
<thead>
<tr>
<th></th>
<th>4350 (RPM)</th>
<th>4380 (RPM)</th>
<th>4773 (RPM)</th>
<th>5370 (RPM)</th>
<th>6260 (RPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration Studies</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acoustic Studies</td>
<td>X</td>
<td>X*</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
ELECTROMAGNETIC FIELD
Current Time History

- Conventional
- Sine Wave

Motor
Motor+Propeller

AOA Trailing Edge Distance

Current Time History

Current (Amps)

Times (sec)

Motor
Motor+Propeller

Current (Amps)

Times (sec)

Motor
Motor+Propeller

Current (Amps)

Times (sec)

Motor
Motor+Propeller

Current (Amps)

Times (sec)
Current Spectra - Unloaded

Conventional
Current Spectra - Unloaded

Conventional

Sine Wave
Current Spectra - Loaded

Conventional

Motor Alone | Harmonics | Motor + Propeller

5370 RPM

6260 RPM
Current Spectra - Loaded

Conventional

Sine Wave

5370 RPM

6260 RPM
MOTOR VIBRATION
Static Measurements

<table>
<thead>
<tr>
<th>Motor</th>
<th>Rotor Frequency (Hz)</th>
<th>Motor Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DJI 2212 (1)</td>
<td>4900</td>
<td>5000</td>
</tr>
<tr>
<td>DJI 2212 (2)</td>
<td>5010</td>
<td></td>
</tr>
<tr>
<td>DJI 2312</td>
<td>5060</td>
<td></td>
</tr>
<tr>
<td>3DR</td>
<td>4460</td>
<td></td>
</tr>
</tbody>
</table>

- Accelerometer 1
- Accelerometer 2

Motor Rotor Frequency (Hz) Motor Frequency (Hz)
DJI 2212 (1) 4900 5000
DJI 2212 (2) 5010
DJI 2312 5060
3DR 4460

Deflected - Undeflected

0 0.002 0.004 0.006
Time (sec)
Dynamic Measurements

Mode 1
- Simulated
  - Simulated Displacement
  - Motor Rotation

Mode 2
- Simulated
  - Simulated Displacement
  - 2*Motor Rotation

Mode 1
- Measured
  - Filtered Time Series
  - Motor Rotation

Mode 2
- Measured
  - Filtered Time Series
  - 2*Motor Rotation

Motor: 4350 Hz
Rotor: 1200 Hz

Motor: 5370 Hz
Rotor: 4600 Hz
Finite Element Results

Mode 1 ~ 1.5 kHz

Mode 2 ~ 4 – 5 kHz

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Frequency (Hz) Mode 1</th>
<th>Frequency (Hz) Mode 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static Rotor with Adhesive</td>
<td>1230</td>
<td>5020</td>
</tr>
<tr>
<td>Static Rotor without Adhesive</td>
<td>1230</td>
<td>5270</td>
</tr>
<tr>
<td>Rotor at 4350 RPM</td>
<td>1390</td>
<td>4650</td>
</tr>
<tr>
<td>Rotor at 5370 RPM</td>
<td>1390</td>
<td>4650</td>
</tr>
</tbody>
</table>
UNINSTALLED ACOUSTICS
Motor Speed Impact

Conventional

4380 RPM

5370 RPM

6260 RPM

Acoustic
Current
Motor Speed Impact

![Graphs showing sine wave impact at different rpm]

- **4380 RPM**: Sine wave data
- **4773 RPM**: Sine wave data
- **5370 RPM**: Sine wave data
- **6260 RPM**: Sine wave data

Frequency (Hz)

SPL (dB)
Motor Impact

Conventional

DJI 2212

3DR

DJI 2312
Loading Impact

Conventional

- 4380 RPM
- 5370 RPM
- 6260 RPM

Motor
Motor + Propeller

SPL (dB)

Frequency (Hz)

0 1000 2000 3000 4000 5000 6000 7000 8000 9000 10000
Loading Impact

Sine Wave

4380 RPM

4773 RPM

5370 RPM

6260 RPM
INSTALLED ACOUSTICS
Installed Acoustic Radiation

Conventional

<table>
<thead>
<tr>
<th>RPM</th>
<th>Isolated</th>
<th>Installed</th>
</tr>
</thead>
<tbody>
<tr>
<td>4380</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5370</td>
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<td>6260</td>
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<td></td>
</tr>
</tbody>
</table>
Conclusions

• Increased harmonic content of the current signal results in increased harmonic content of the pressure loading from the stator magnetic field

• Conventional and sine wave controllers produce significant harmonic content in the current signal

• Controllers can also produce non-harmonic discrete current peaks

• Mode 1 and 2 vibrations of the rotor occurred at 1 – 1.5 kHz and 4.4 – 5.1 kHz, respectively

• Significant acoustic radiation occurs for most configurations and speeds at frequencies near the mode 2 vibration frequency

• For some configurations and speeds, acoustic radiation occurs near the mode 1 vibration frequency

• Loading the motor increases acoustic radiation for some conditions and configurations

• Installing the motor increases acoustic radiation at frequencies near the mode 1 frequency