



Update on Electric Motor Noise Measurements and Predictions

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NASA Acoustics Technical Working Group

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Objectives and Approach



- Objectives
 - Determine relative importance of electric motor noise
 - Develop electric motor noise predictive tool that can be used in future system predictions
- Approaches
 - Empirical – formulas exist but were not developed for motors of interest
 - Analytical – simplified theories have been previously developed and applied with some success
- RVLT Milestones
 - RVLT.23.21.L485 Assessment of small UAS electric motor noise
 - RVLT.23.21.L334 Small electric motor noise tool for ANOPP2



Electric Motor Noise Theory

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

$$p_R(\alpha, t) = \frac{1}{2\mu_0} [b_R^2(\alpha, t) - b_T^2(\alpha, t)] \leftarrow \text{small - ignore}$$

b = magnetic flux density

μ_0 = magnetic permeability = constant

$$b_T \ll b_R$$

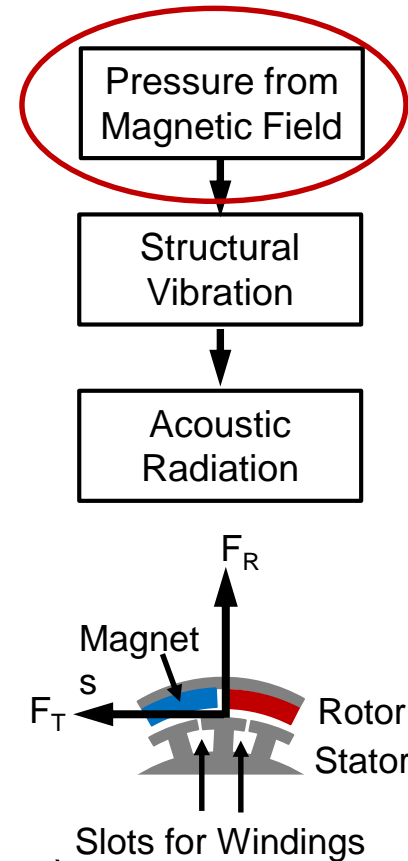
$$b_R = b_{Rpm} + b_{RS}$$

Stator
↓
↑
Rotor

- Resulting radial pressure on outer surface (rotor in this case)

$$p_R(\alpha, t) \approx \frac{1}{2\mu_0} [b_{Rpm}^2(\alpha, t) + 2b_{Rpm}(\alpha, t)b_{RS} + b_{RS}^2(\alpha, t)]$$

↑ Rotor Field
 ↑ Rotor-Stator Interaction
 ↑ Stator Field



Electric Motor Noise Theory (con't)



Pressure from Magnetic Field

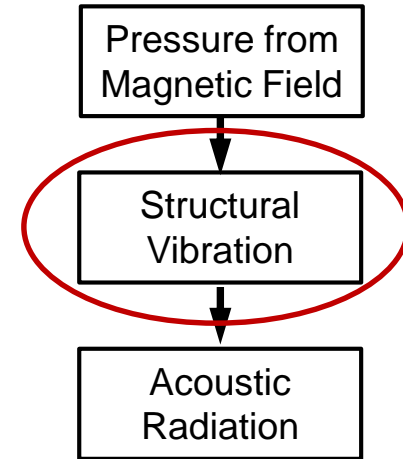
- Field associated with permanent magnets (b_{Rpm})
 - Geometry (out-running/in-running, radius, gap distance, # poles, etc.)
 - Magnet properties
- Field associated with Stator (b_{RS})
 - Geometry (radius, gap distance, # slots, slot opening, etc.)
 - Winding scheme (winding distribution factor, turns/phase, coil span, etc.)
 - Load (current)

Electric Motor Noise Theory (con't)



Structural Vibration

- Thin shell theory (non-rotating)
 - h/R small
 - Several formulations - results are similar
- Thin shell theory with stiffeners (stringers)
 - Distributed mass works reasonably well for large numbers of stringers covering large portion of shell
- Thin rotating shell
 - Rotation increases natural frequencies relative to non-rotating shell – increase depends on speed and mode



Electric Motor Noise Theory (con't)



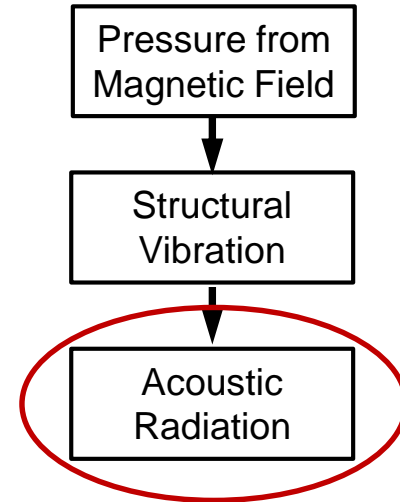
Acoustic Radiation

- Approaches

- Infinite cylinder
- Finite cylinder with rigid baffles
- Simplified numerical calculation

- On acoustic boundary

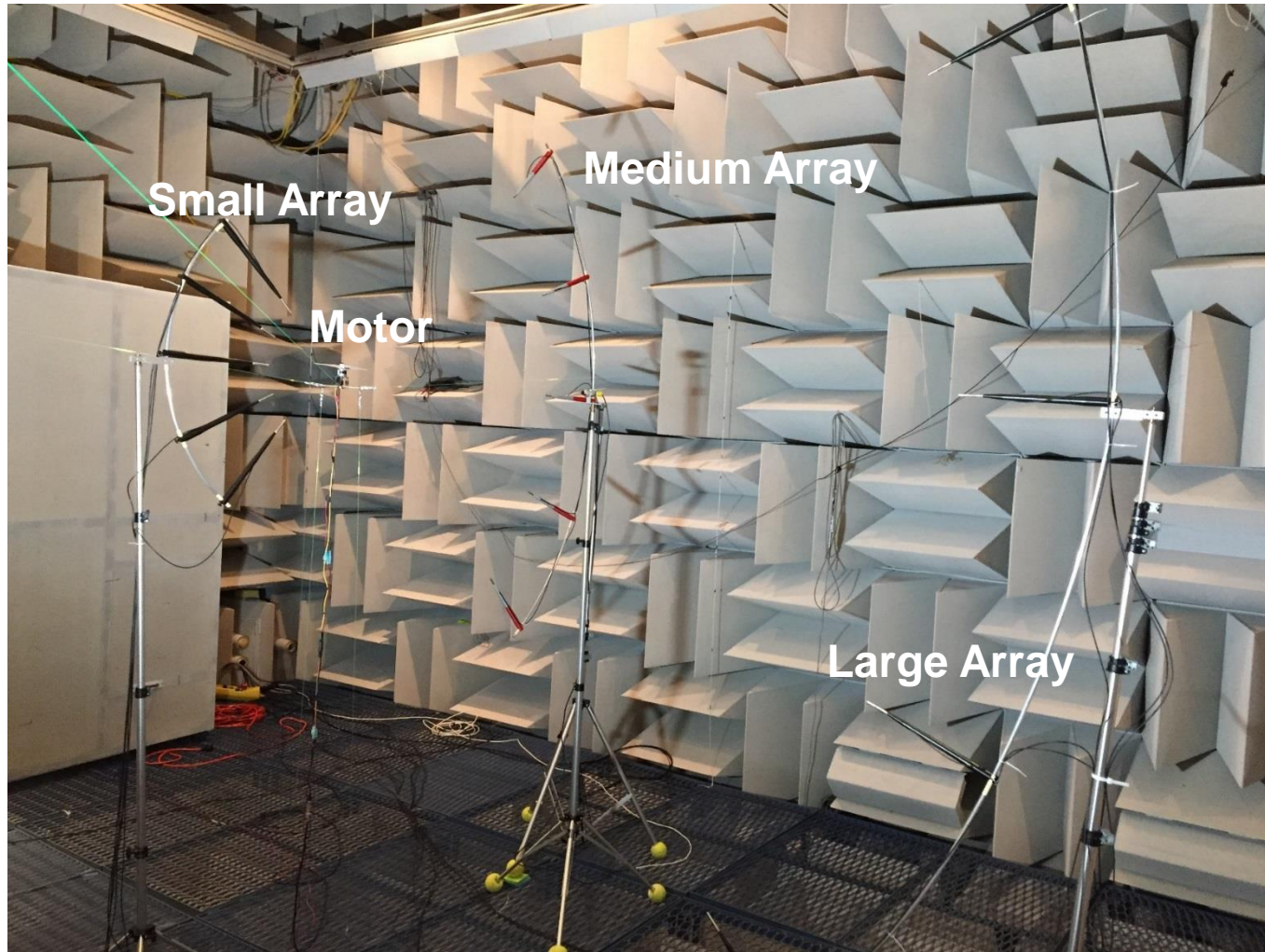
- Frequency
 - Only need to predict radiation in relevant frequency bands
 - Relevant frequency bands depend on structural response and noise perception
- Displacement for relevant modes



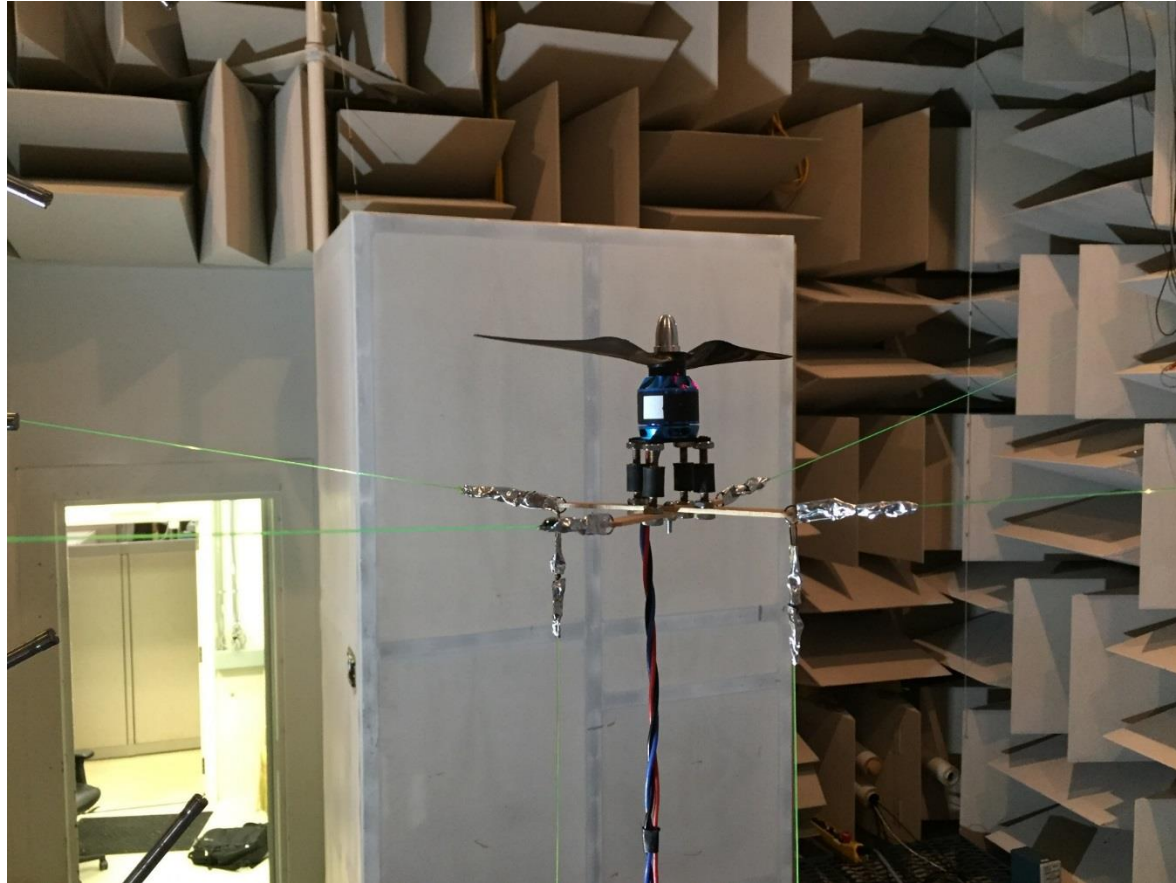


**Is electric motor noise
important?**

Experimental Setup



Motor and Propeller with Tether



Test Matrix



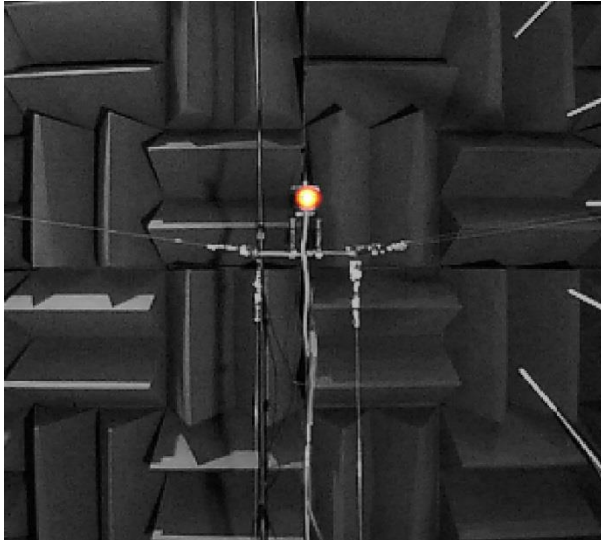
	3DR "Blue"	2212	2312
Speed Variation (RPM)	4380, 5370, 6260	4380, 5370, 6260, 4773	4380, 5370, 6260, 4773
Acoustics (Small, Medium, Large Arrays)	X	X	X
Speed Controllers			
E300	X	X	X
3DR	X	X	-
420S	-	X	X
Load			
Motor Only	X	X	X
2-Bladed	X	X	X
3-Bladed	-	-	X
Phased Array	X (location study)	X	X
Current Probe	2 loops	1 loop	1 loop
Ping Test	X	X	X
Motor kV Constant (1/Ke)	850	920	960



Phased Array Results - 5029 Hz



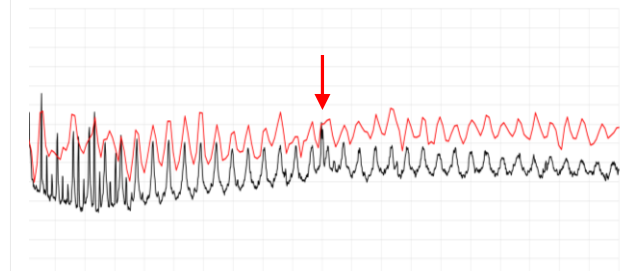
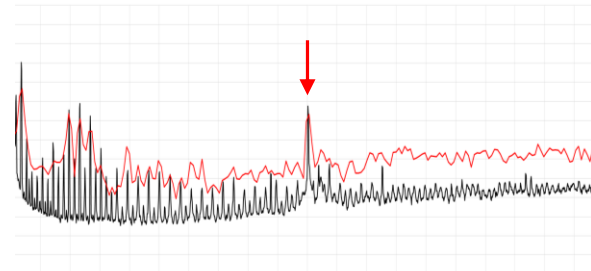
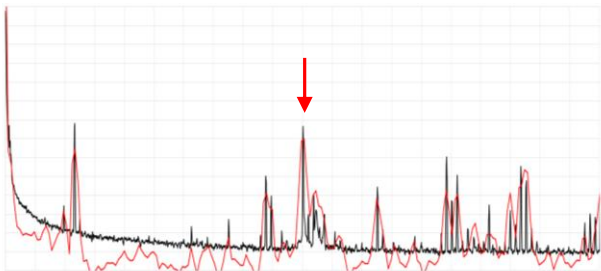
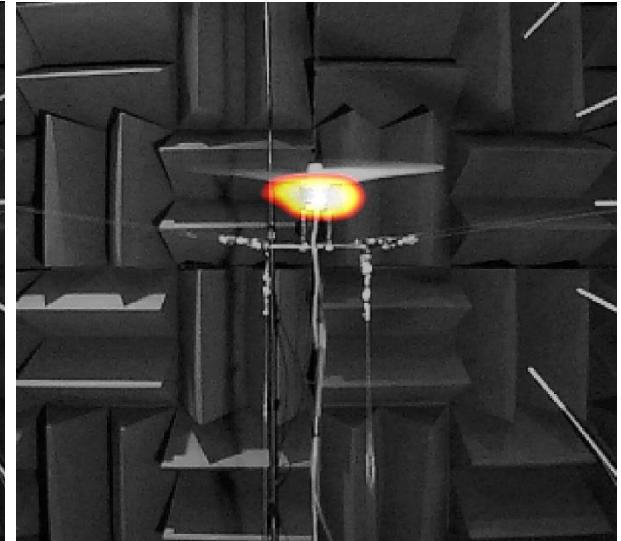
Motor Only



2-Bladed Propeller



3-Bladed Propeller

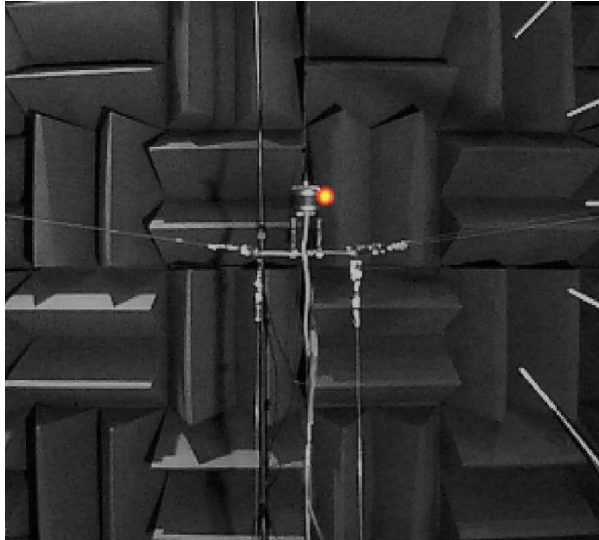


— 90° Microphone
— Phased Array Microphone

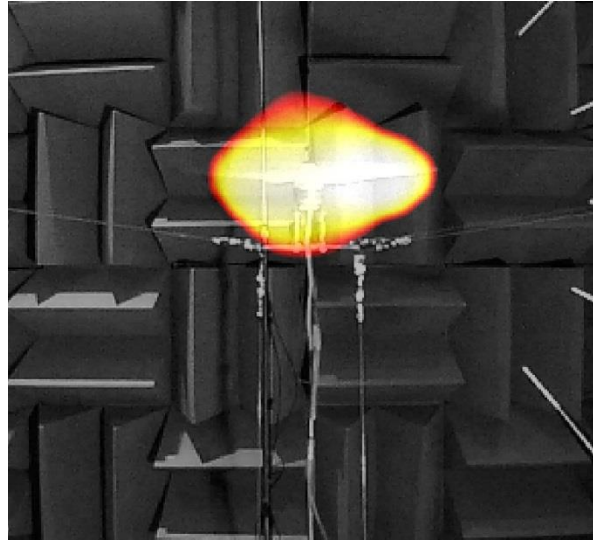
Phased Array Results - 6885 Hz



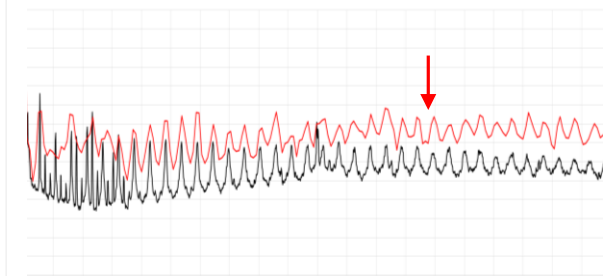
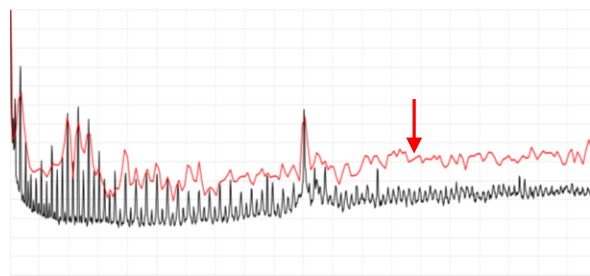
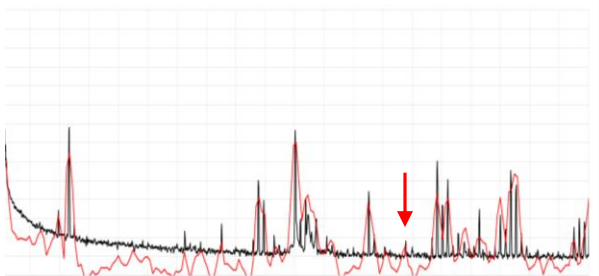
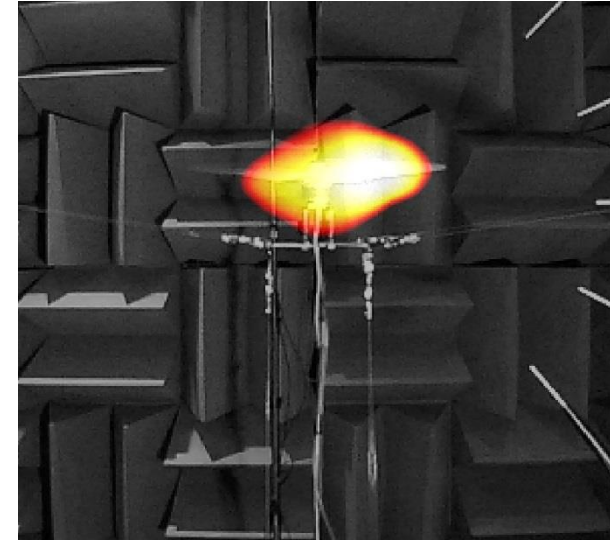
Motor Only



2-Bladed Propeller



3-Bladed Propeller



— 90° Microphone
— Phased Array Microphone



Analytical Tool Development Progress

Relevant Motor and Controller Parameters

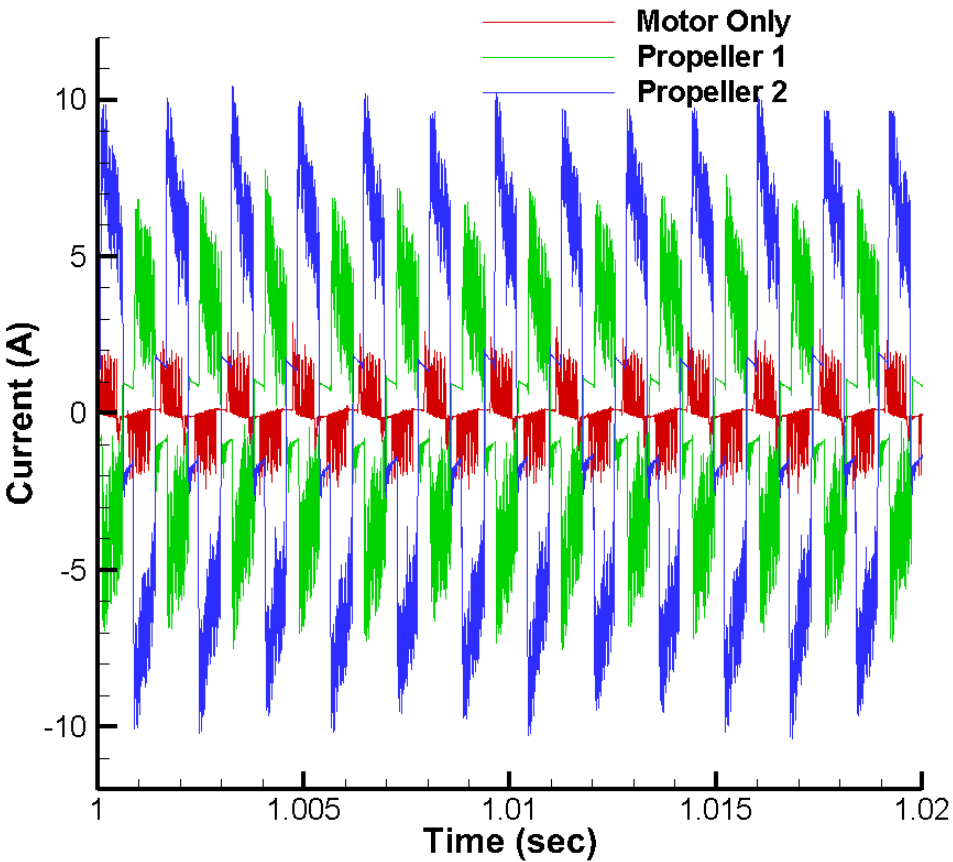


- Motor winding topology
 - dLRK – very common for outrunning model motors
- Controllers
 - Pulse position modulation (PPM) at
 - 50 Hz (PPM) signal produces pulse width modulation at 10 – 20 kHz
 - Duty cycle of PPM related to speed
 - Two types of controllers
 - Conventional – ~square wave provided to motor
 - Sinusoidal - ~sinusoidal wave provided to motor

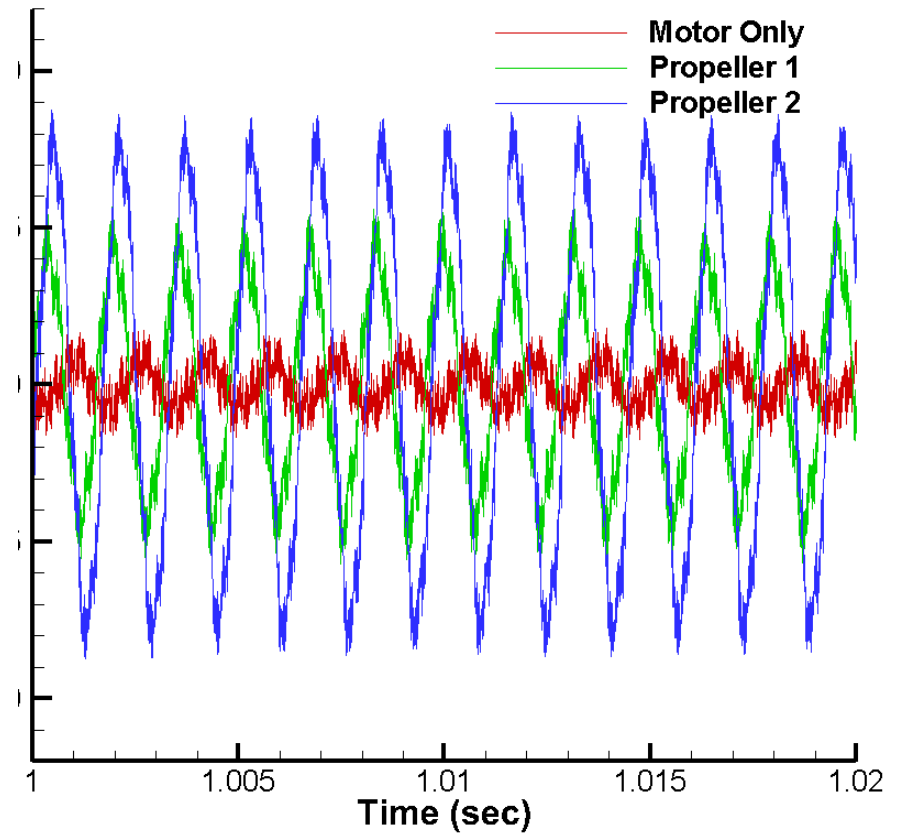
Current Waveforms (Magnetic Field)



Conventional Controller



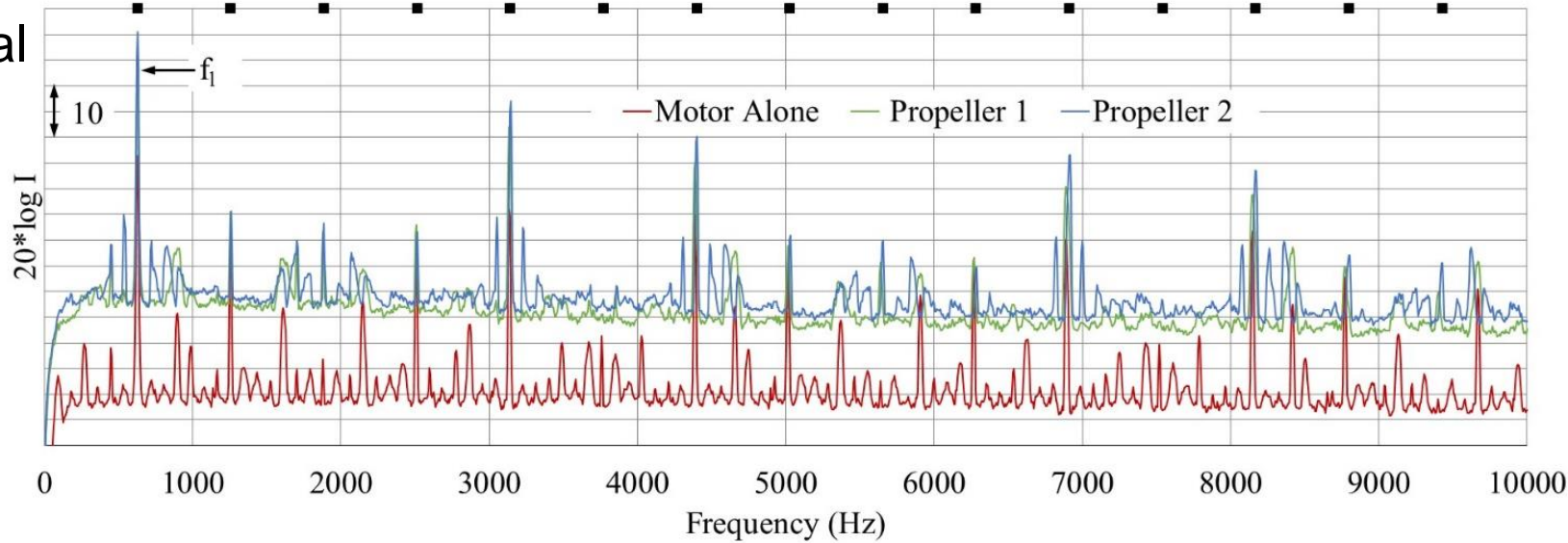
Sine Wave Controller



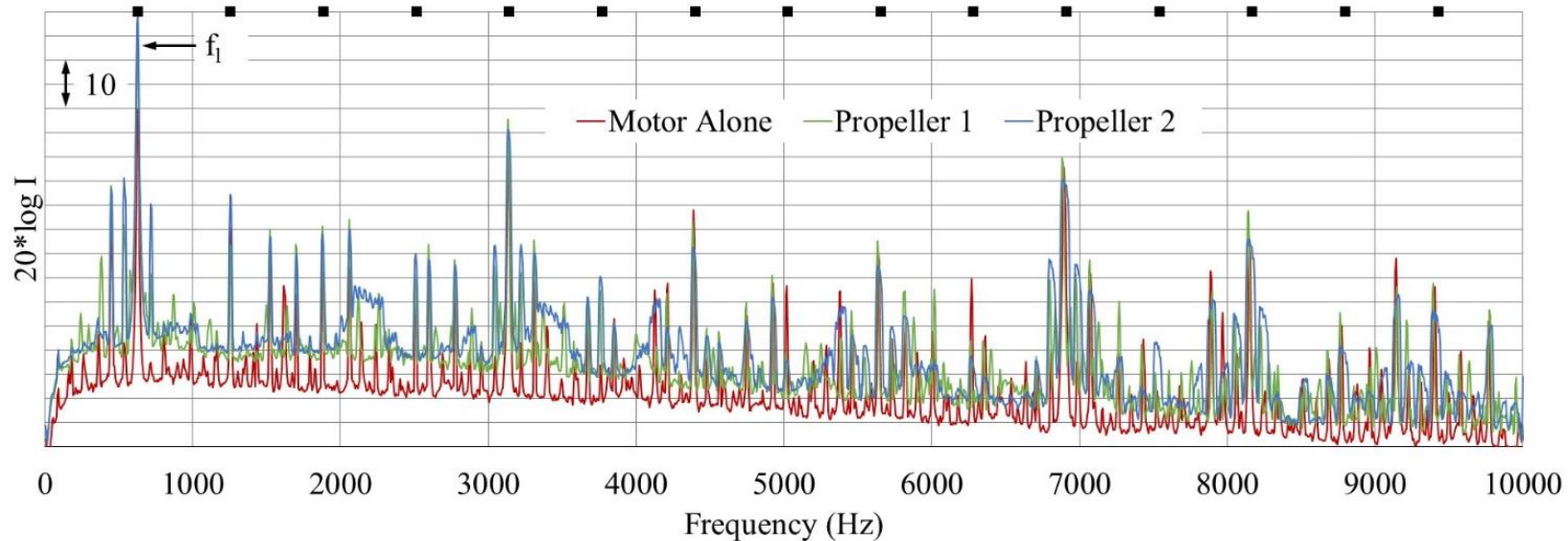
Current Waveforms (con't)



Conventional

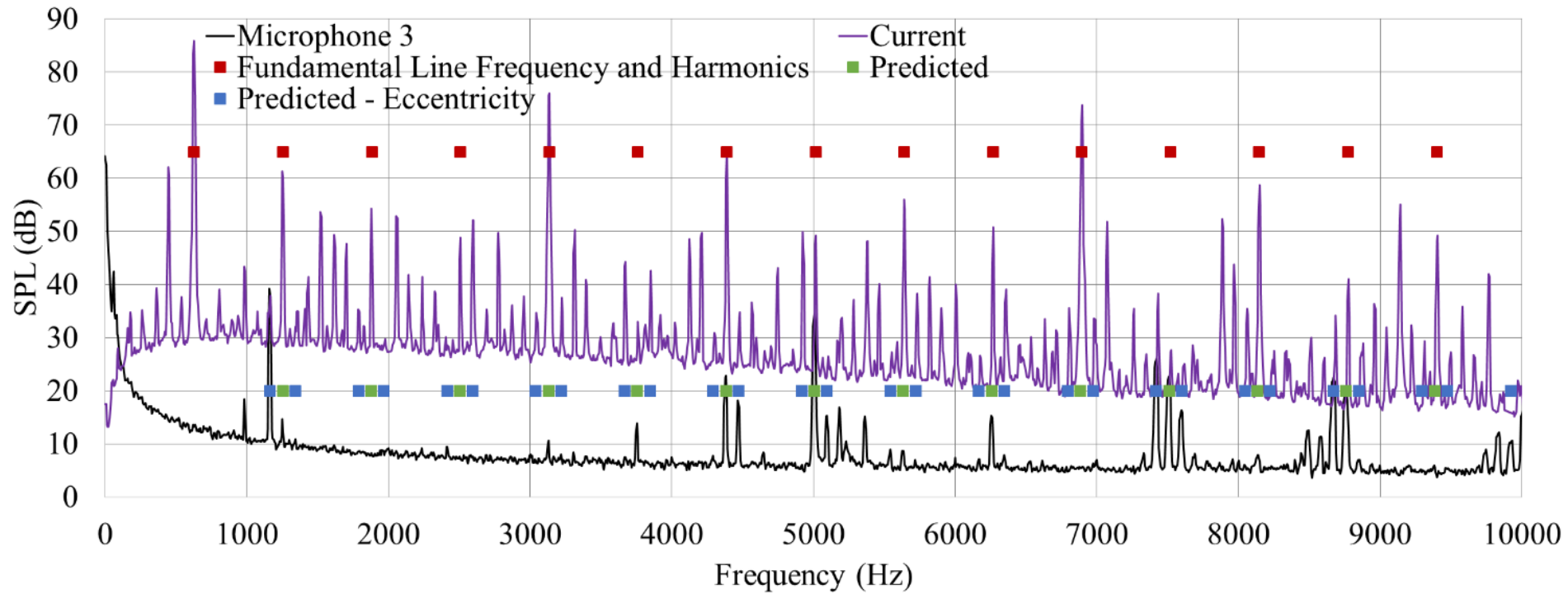


Sine Wave

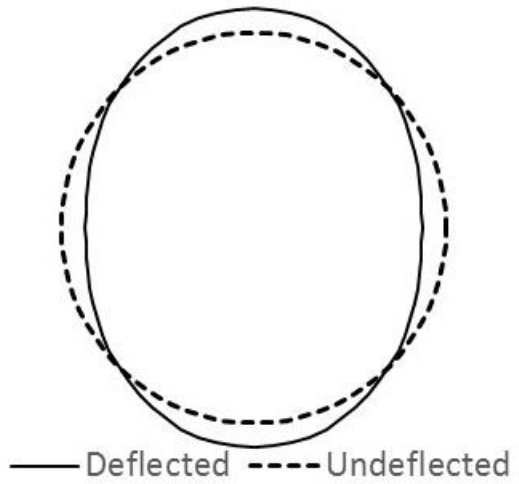
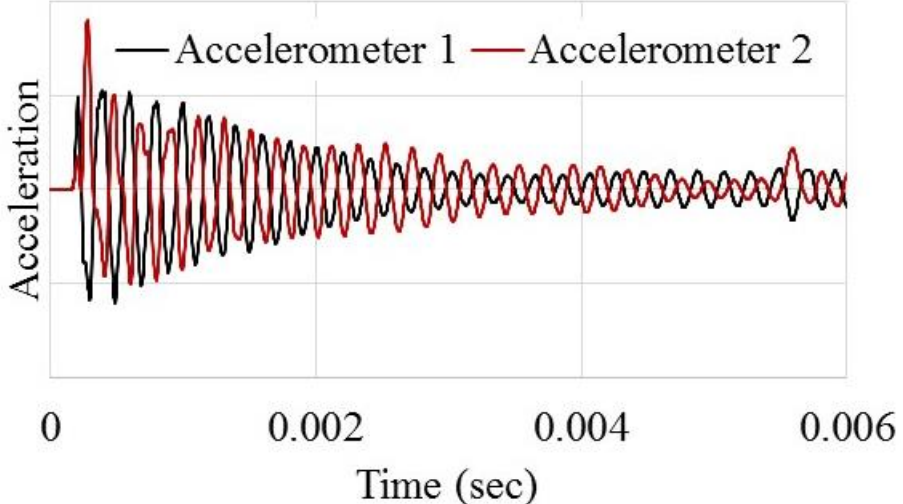




Acoustic Field – Sine Wave Controller



Static Motor Tests (Structural Vibration)

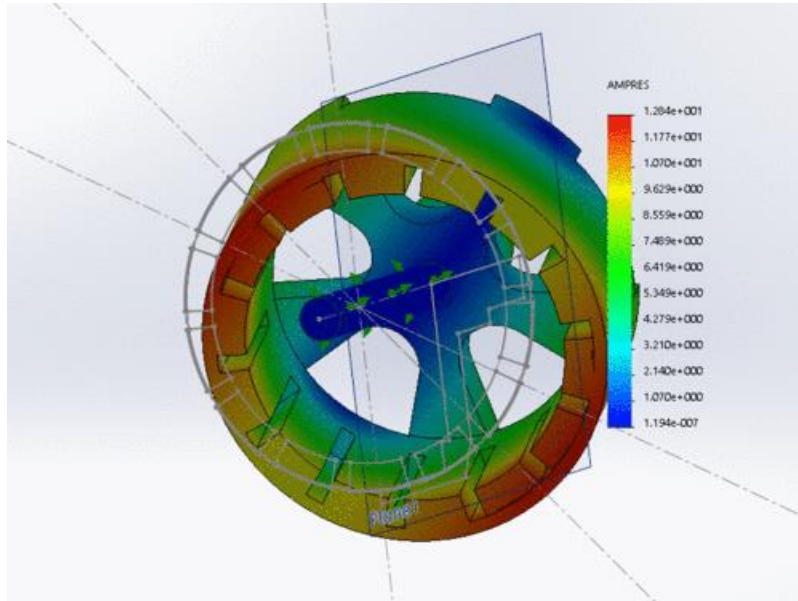


Motor	Rotor Frequency (Hz)	Motor Frequency (Hz)
DJI 2212 (1)	4900	5000
DJI 2212 (2)		5010
DJI 2312		5060
3DR		4460

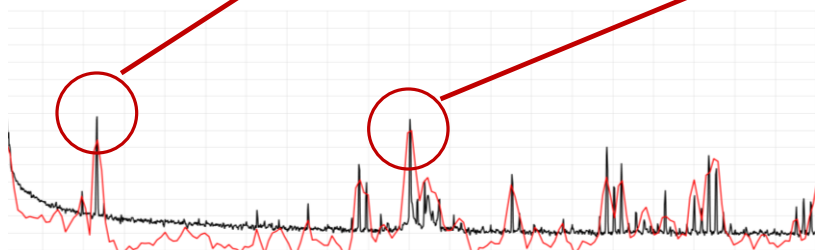
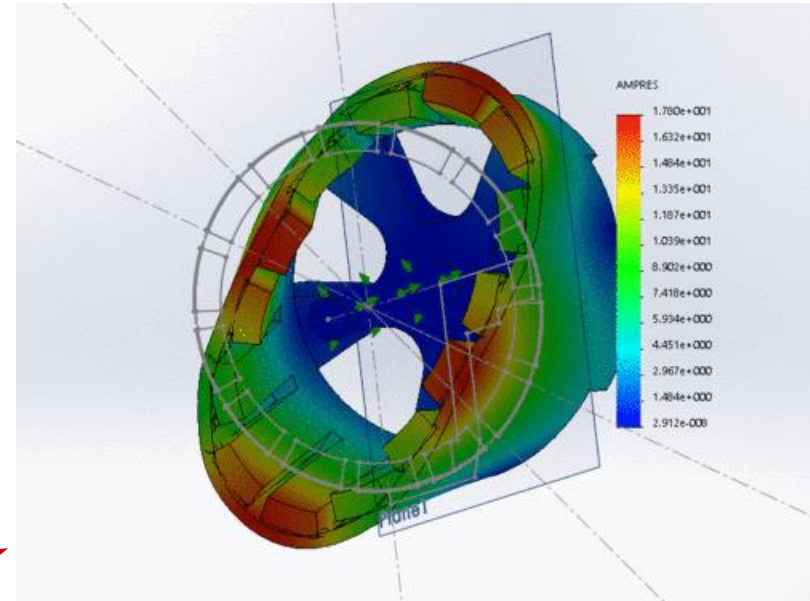
Finite Element Analysis



Mode 1 ~ 1.5 kHz



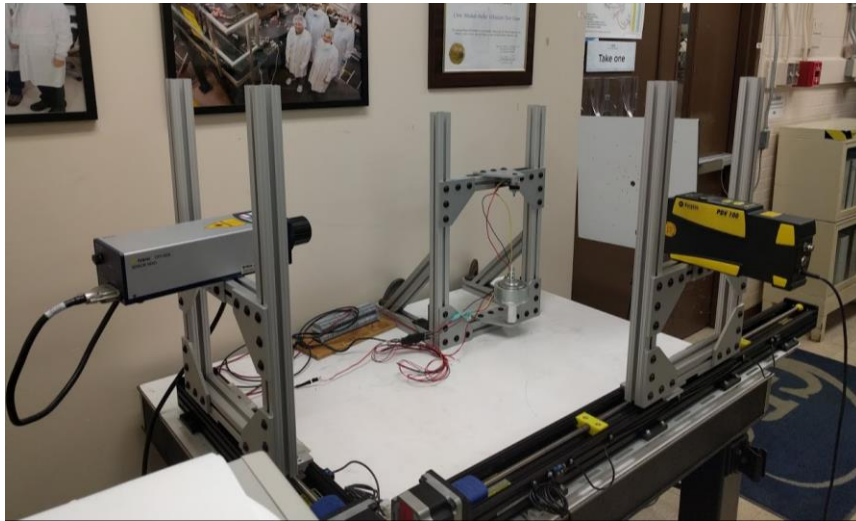
Mode 2 ~ 4 – 5 kHz



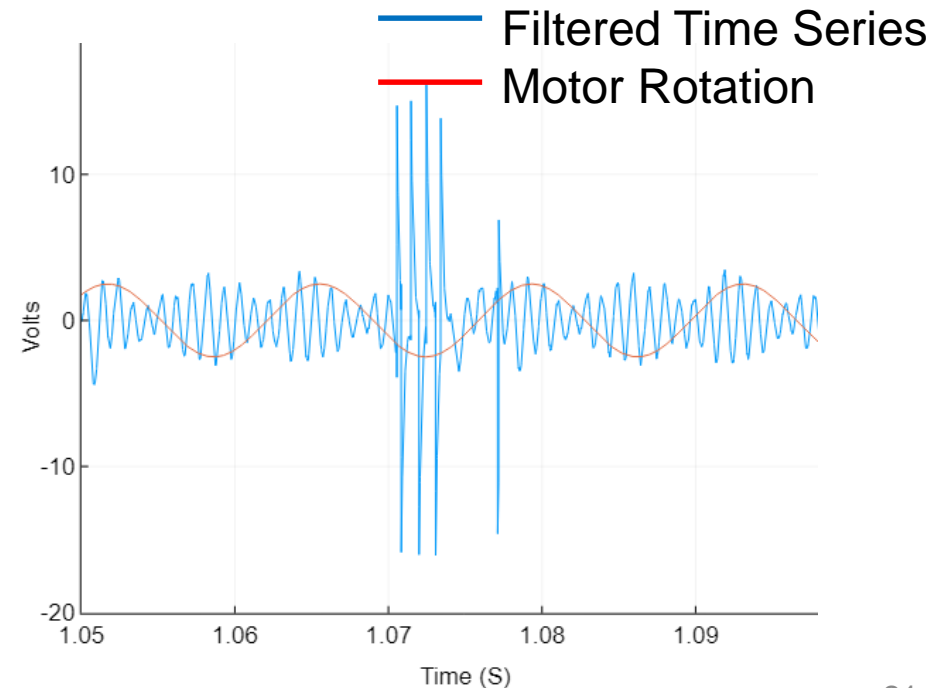
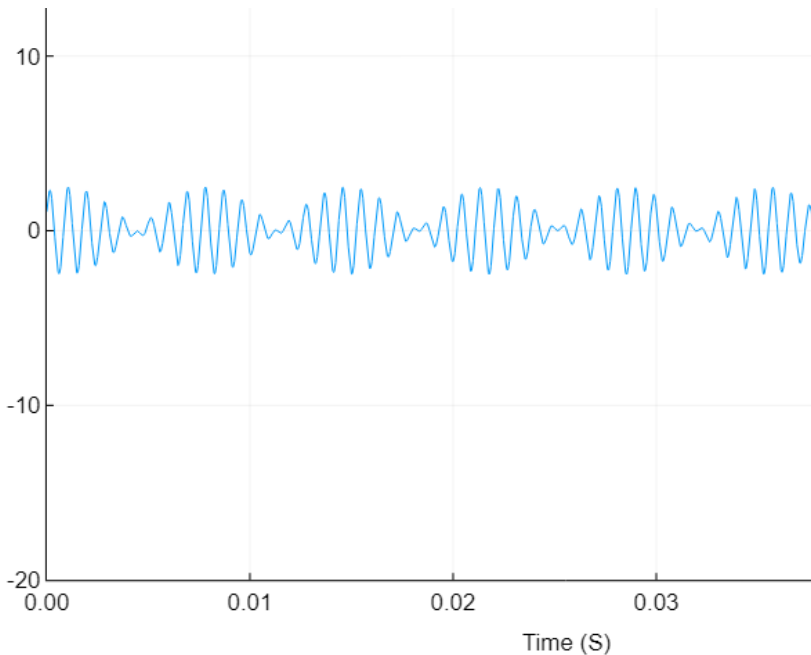
Mode 2

Analytical Theory	Frequency
Thin Shell - Static	~ 40 kHz
Thin Shell - Rotating	~ 39 kHz
Thin Shell - Stringer Stiffened (Static)	~ 38.5 kHz

Displacement Measurements (Vibration)



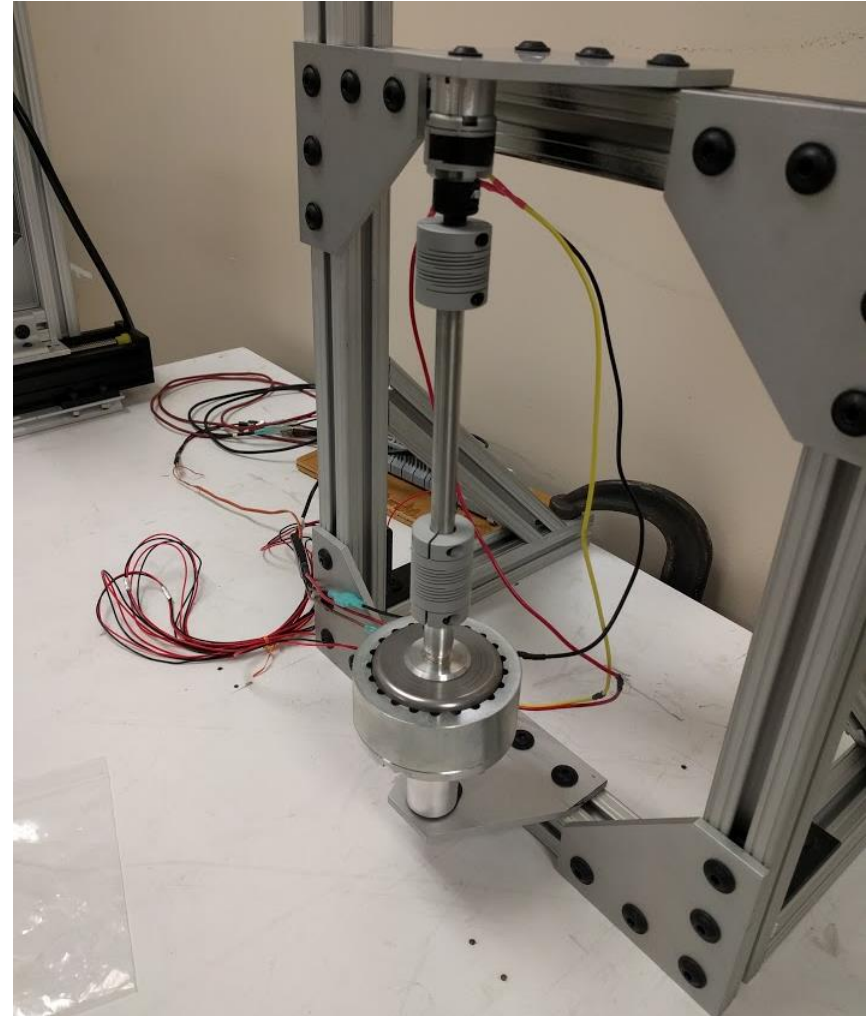
- Mode 1 frequency close to that predicted in FEA and measured in acoustic field $\sim 5 \mu\text{m}$ amplitude
- Mode 2 measured at higher motor speed $\sim 0.4 \mu\text{m}$ amplitude
- Still resolving laser alignment issues



Quiet Loading



- Magnetic Technologies
EB140M eddy current brake
- Vertical orientation
- Extension shaft and 2 flex couplings
- Operates quietly up to ~3600 rpm



Conclusions and Future Plans (UASs)

Conclusions

- Electric motors contribute to the overall acoustic radiation
- Electric motor noise increases with loading – quiet loading approach is challenging
- All controller produce multiple harmonics and, therefore, will likely excite tones at 4 – 5 kHz
- Peak acoustic radiation occurs at ~ 1.2 kHz (mode 1) and 4 – 5 kHz (mode 2) for all controllers and motors tested
- Frequencies are not well predicted by thin shell theories
- Amplitude measurements are possible – laser alignment challenging

Future Plans

- Continue investigating noise models for electric motors
- Improve loading scheme – look at balancing loading
- Continue improvements on laser vibrometer measurements
- Conduct measurements on larger motors