National Aeronautics and Space Administration

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





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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

$$p_R(\alpha,t) = \frac{1}{2\mu_o}\left[b_R^2(\alpha,t) - \boxed{b_T^2(\alpha,t)}\right] \longleftarrow \text{small - ignore}$$

b = magnetic flux density

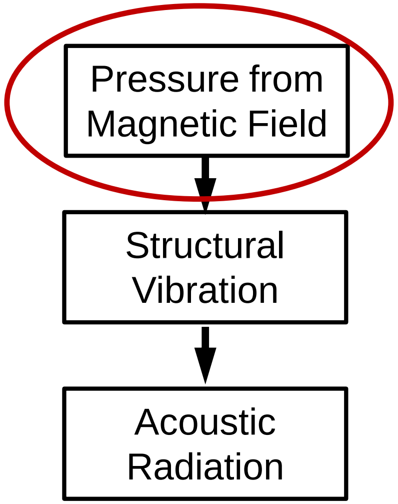
μ_o= magnetic permeability = constant

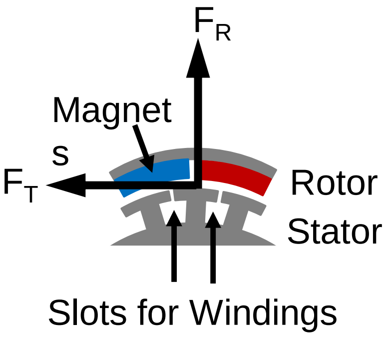
$$b_T \ll b_R$$

$$b_R = \underset{\substack{\uparrow\\ \text{Rotor}}}{b_{Rpm}} + \underset{\substack{\uparrow\\ \text{Stator}}}{b_{Rs}}$$

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

$$p_R(\alpha,t) \approx \frac{1}{2\mu_o}\left[\underset{\substack{\uparrow\\ \text{Rotor}\\ \text{Field}}}{b_{Rpm}^2(\alpha,t)} + \underset{\substack{\uparrow\\ \text{Rotor-Stator}\\ \text{Interaction}}}{2b_{Rpm}(\alpha,t)b_{Rs}} + \underset{\substack{\uparrow\\ \text{Stator}\\ \text{Field}}}{b_{Rs}^2(\alpha,t)}\right]$$





$$f \propto n f_{motor} \propto m f_l$$

$$f_l = {f_{motor}}\big/{\#pole\ pairs\ (N)}$$

Dynamic rotor eccentricity ± qf_l/N

Electric Motor Noise Theory (con’t)

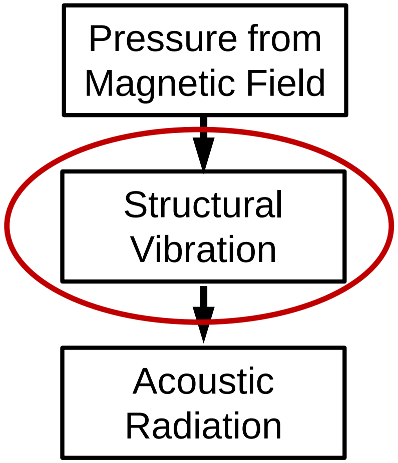
Pressure from Magnetic Field

- 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



Pressure from Magnetic Field

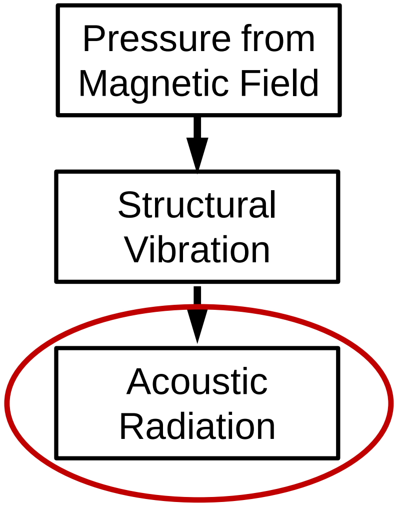
Structural Vibration

Acoustic Radiation

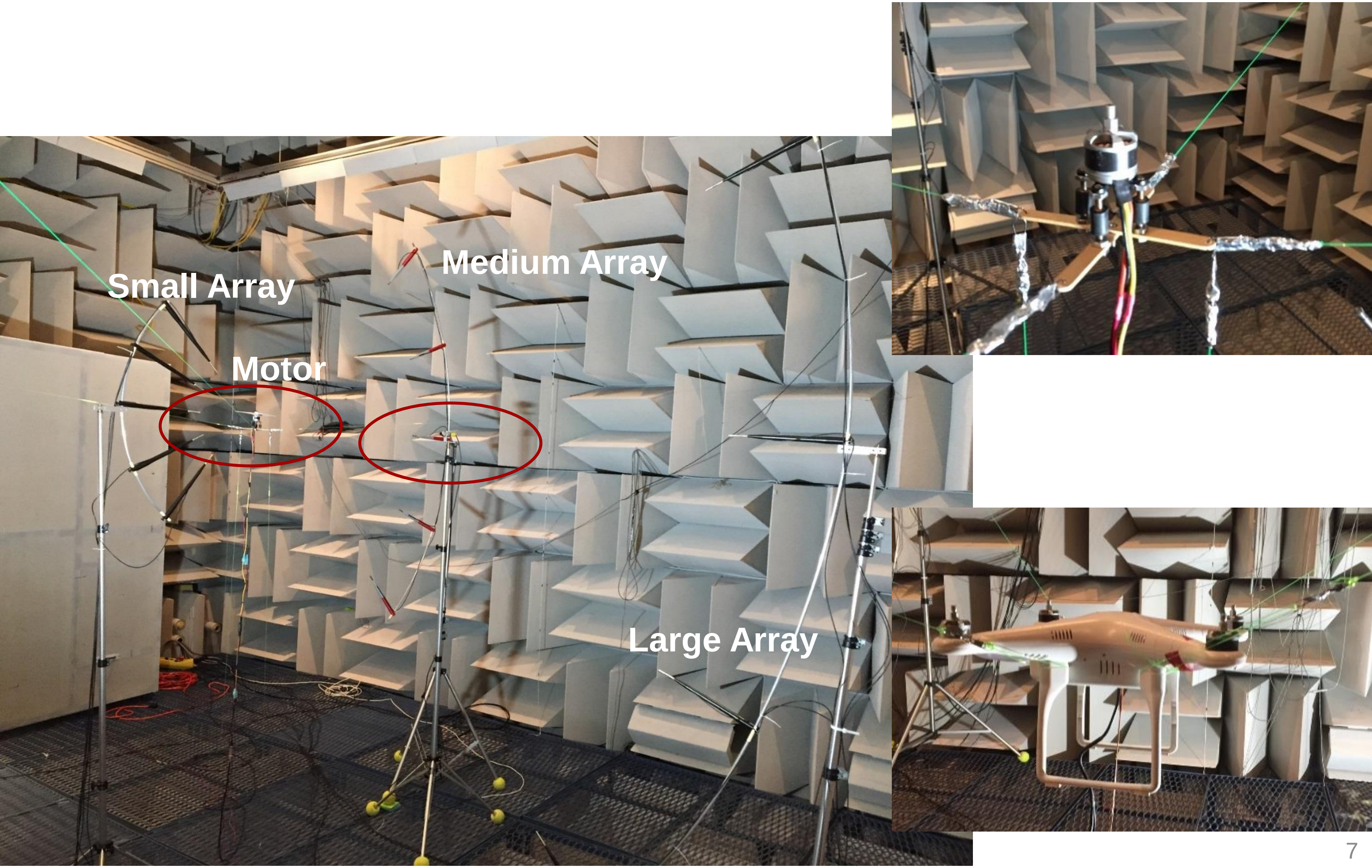
Electric Motor Noise Theory (con't)

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)



Configurations and Conditions

Motors

Manufacturer	Type	K_v	L/D
DJI	2212	920	0.49
DJI	2312	960	0.49
3DR	2830	850	0.54

Dual Strand

Single Strand

Stator Diameter (mm)

Stator Length (mm)

Out-Runner, BLDC Motors

14 Poles, 12 Slots

*Delta **dLRK** or LRK Windings*

$$K_V \propto \frac{1}{K_T} = fxn(\#\ conductors)$$

 # conductors ↑ K_v ↓

Controllers

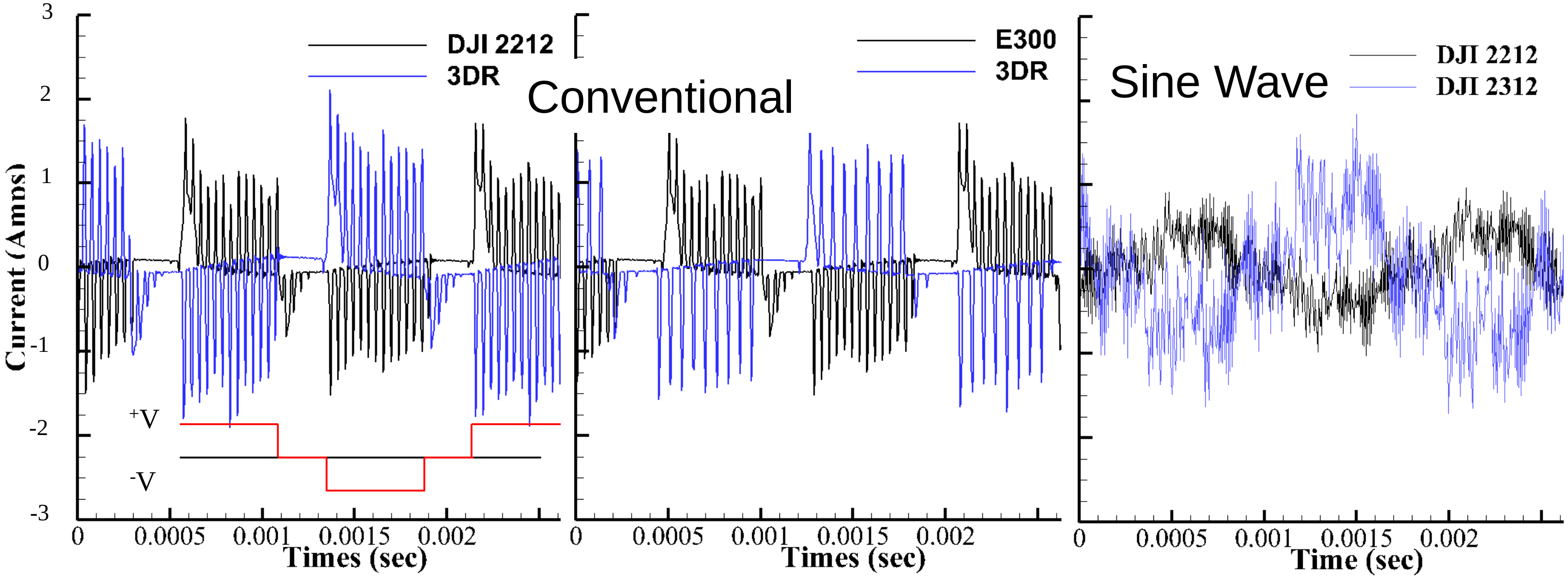
Controller Type	Manufacturer	Model
Conventional	3DR	
Conventional	DJI	E300
Sine Wave	DJI	420S

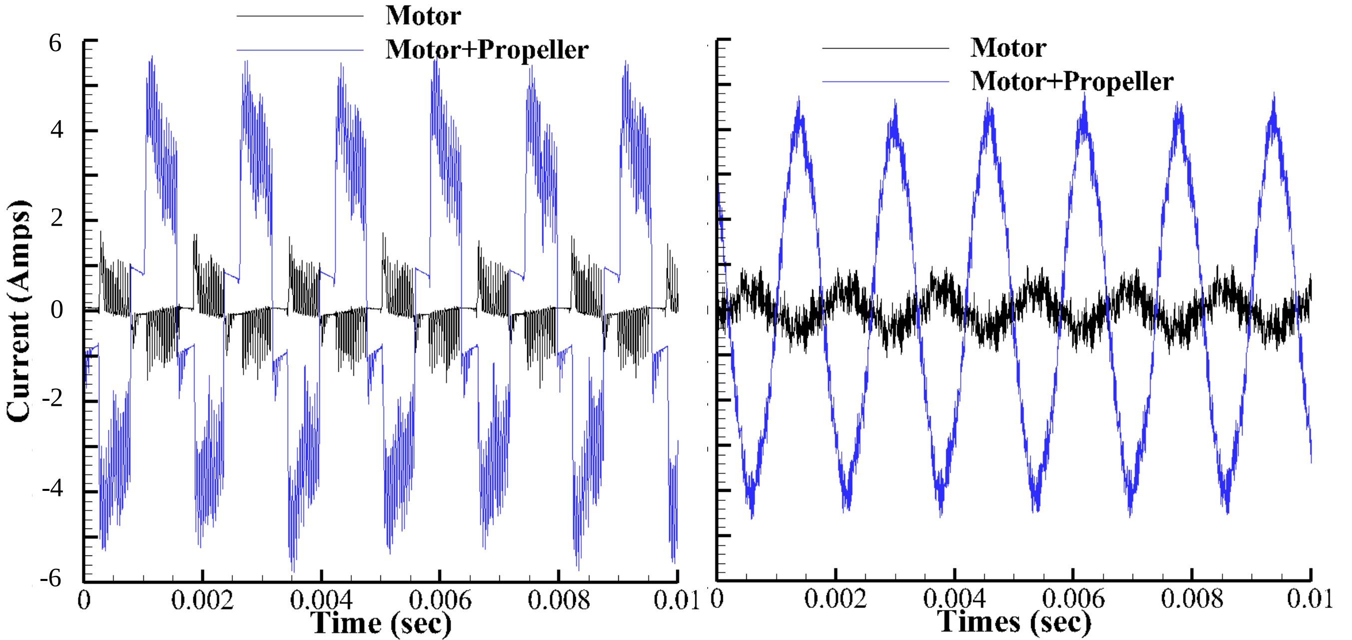
Conditions

	4350 (RPM)	4380 (RPM)	4773 (RPM)	5370 (RPM)	6260 (RPM)
Vibration Studies	X			X	
Acoustic Studies		X	X *	X	X

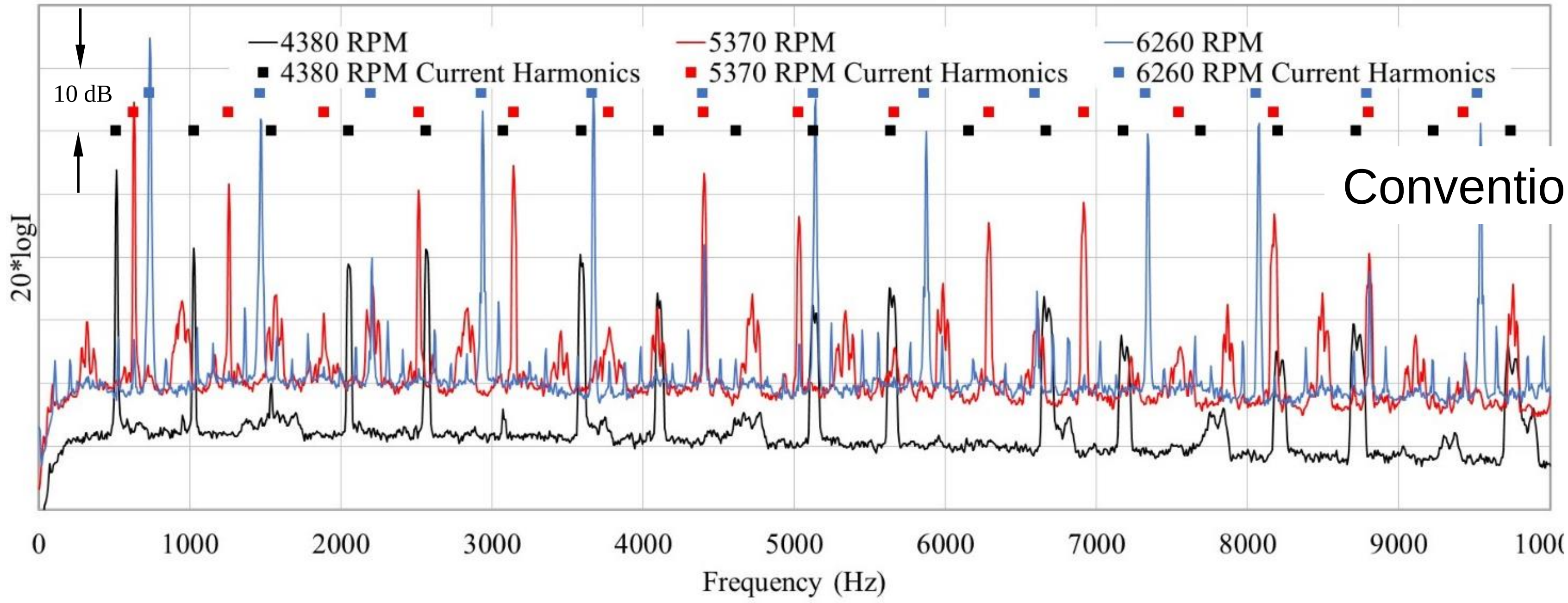
ELECTROMAGNETIC FIELD

Current Time History



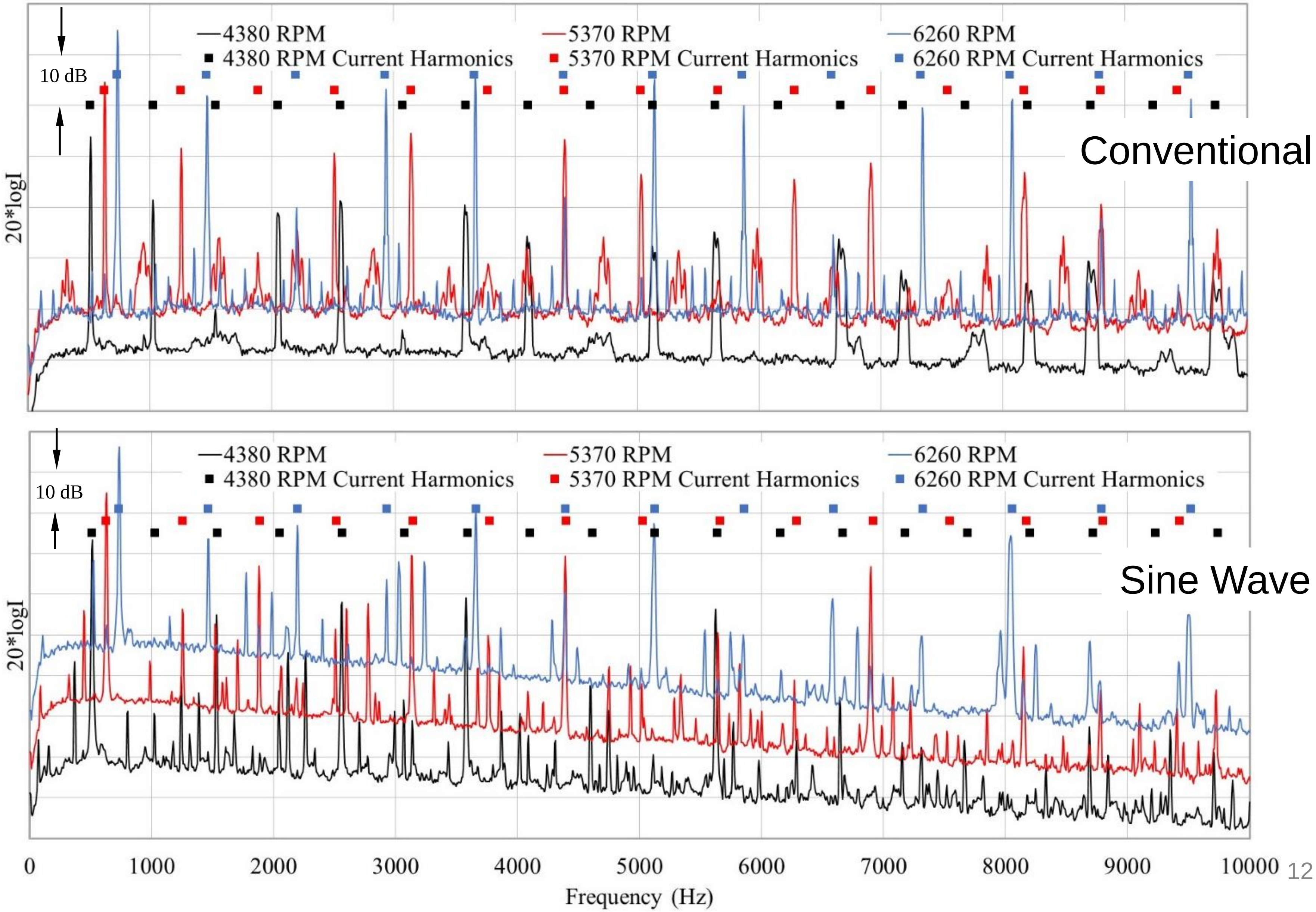


Current Spectra - Unloaded

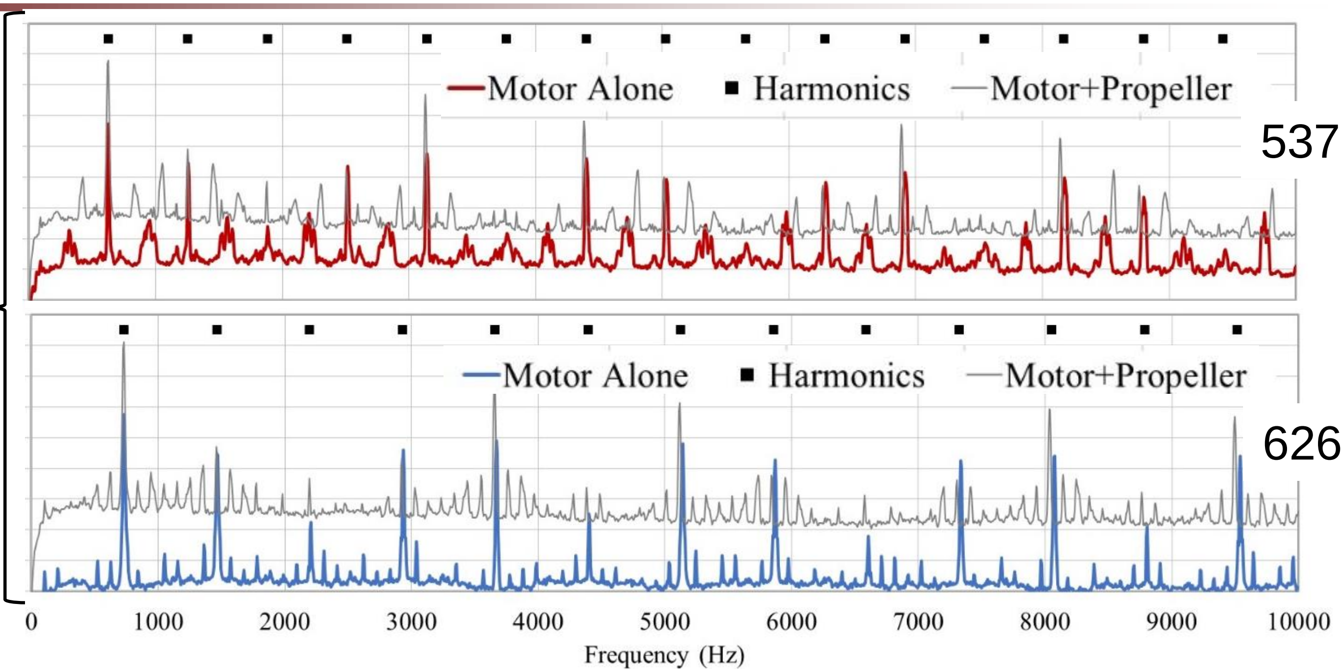


Conventional

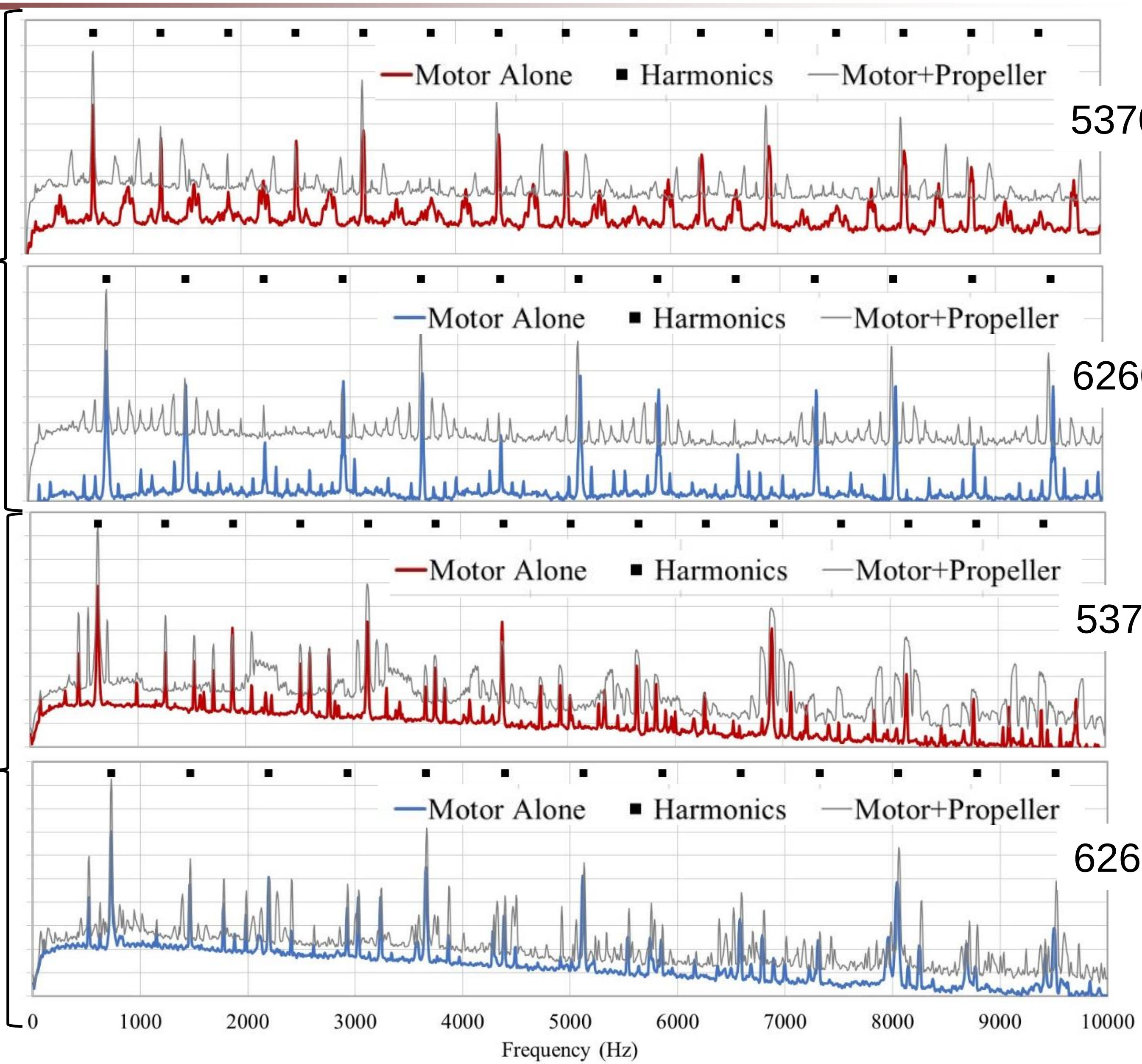
Current Spectra - Unloaded



Current Spectra - Loaded



Current Spectra - Loaded



Conventional

5370 RPM

6260 RPM

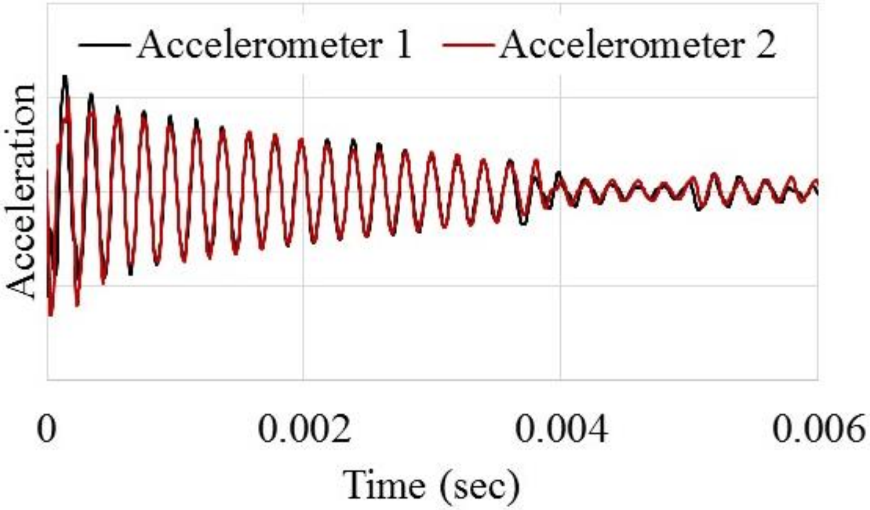
Sine Wave

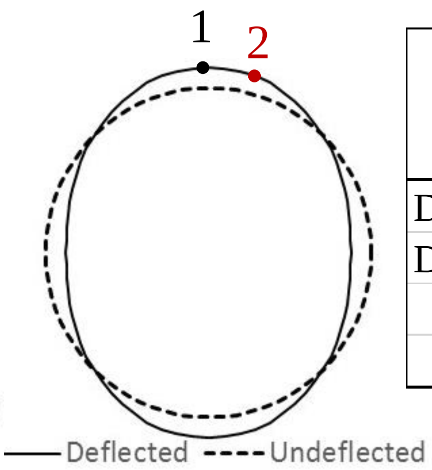
5370 RPM

6260 RPM

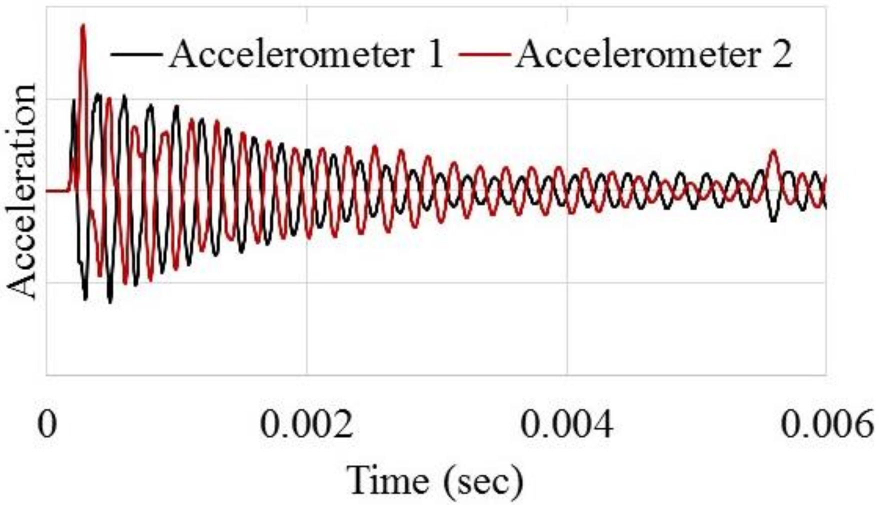
MOTOR VIBRATION

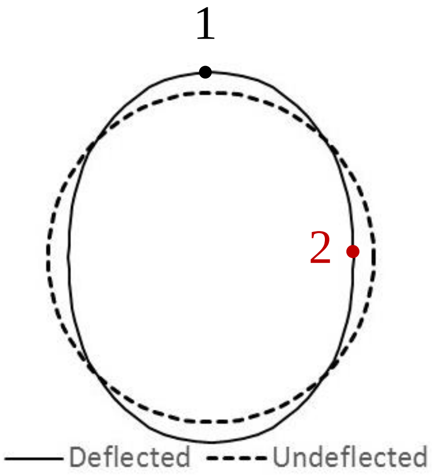
Static Measurements

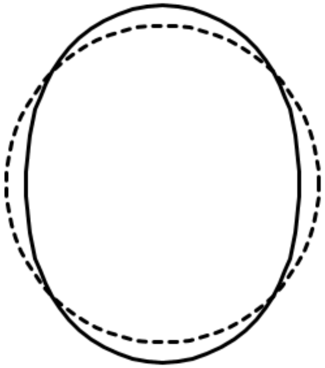




Motor	Rotor Frequency (Hz)	Motor Frequency (Hz)
DJI 2212 (1)	4900	5000
DJI 2212 (2)		5010
DJI 2312		5060
3DR		4460



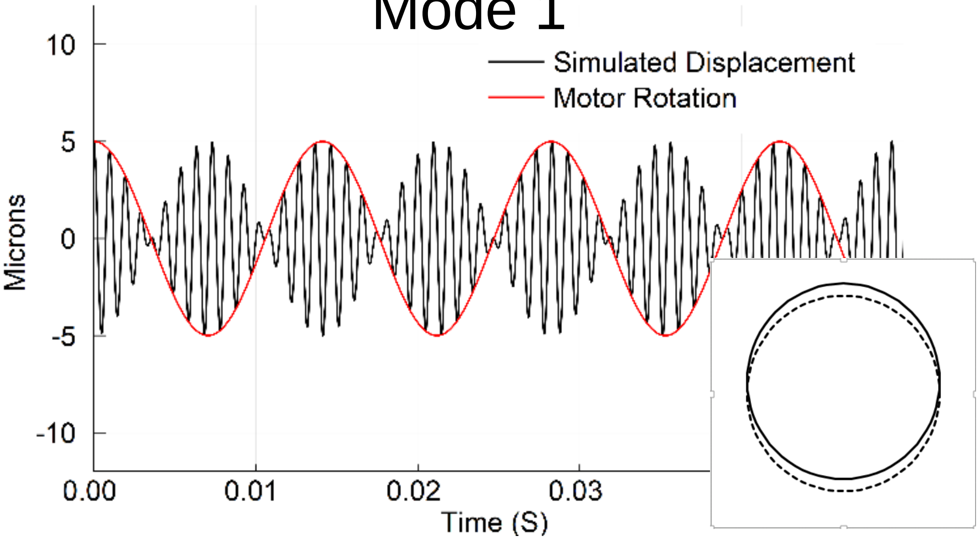




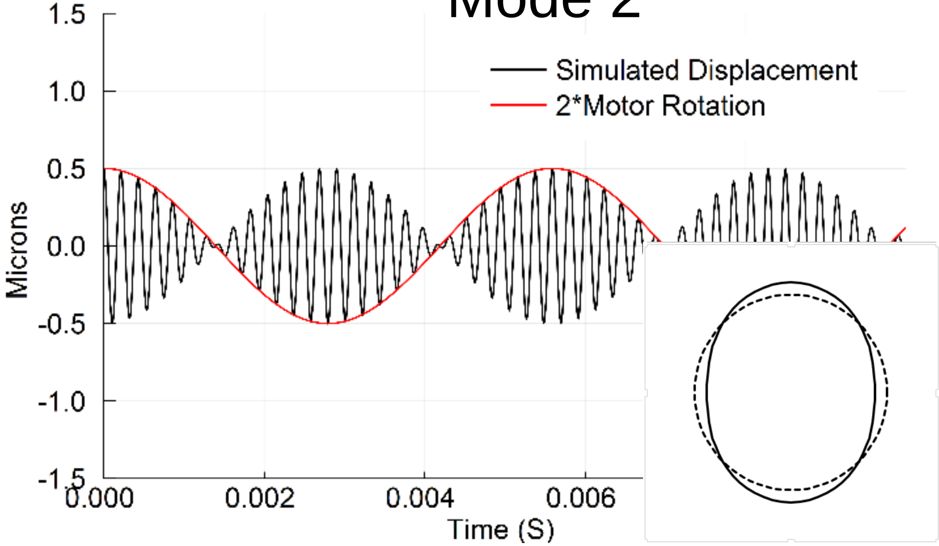
Dynamic Measurements

Simulated

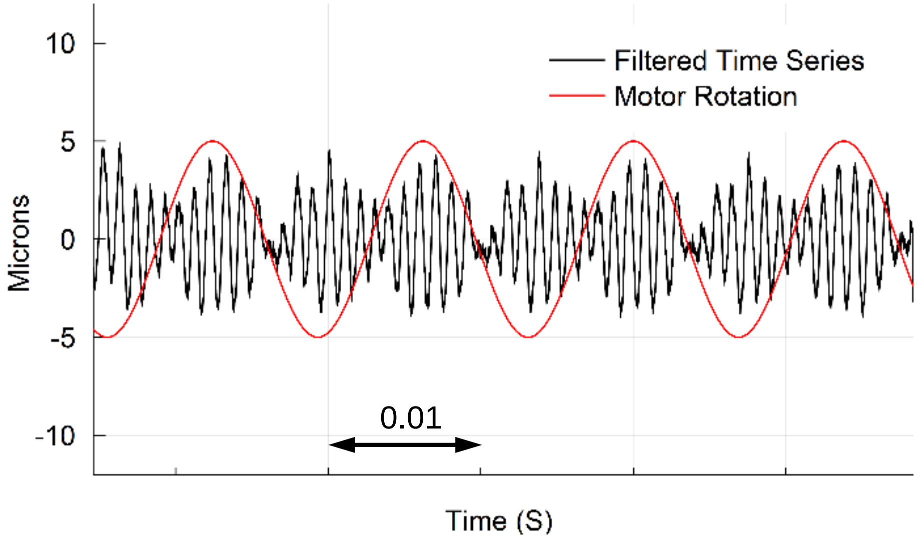
Mode 1

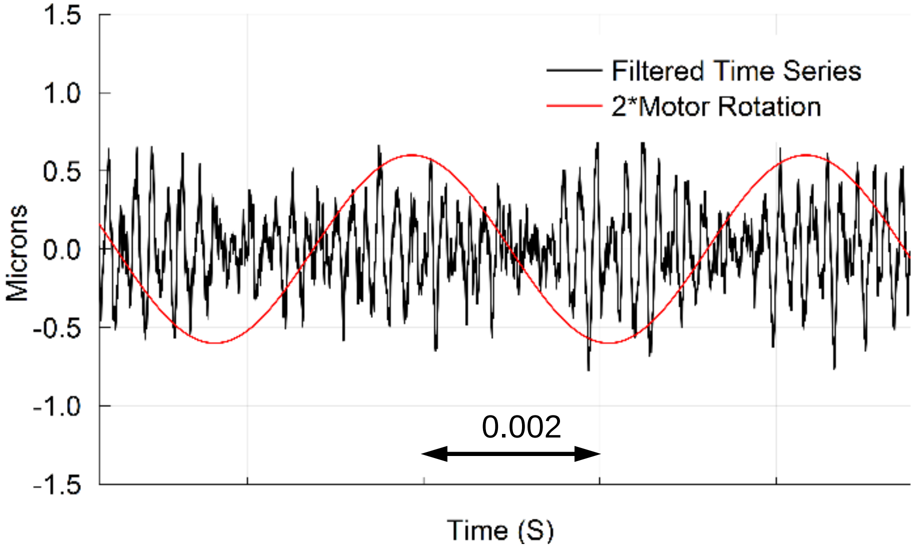


Mode 2



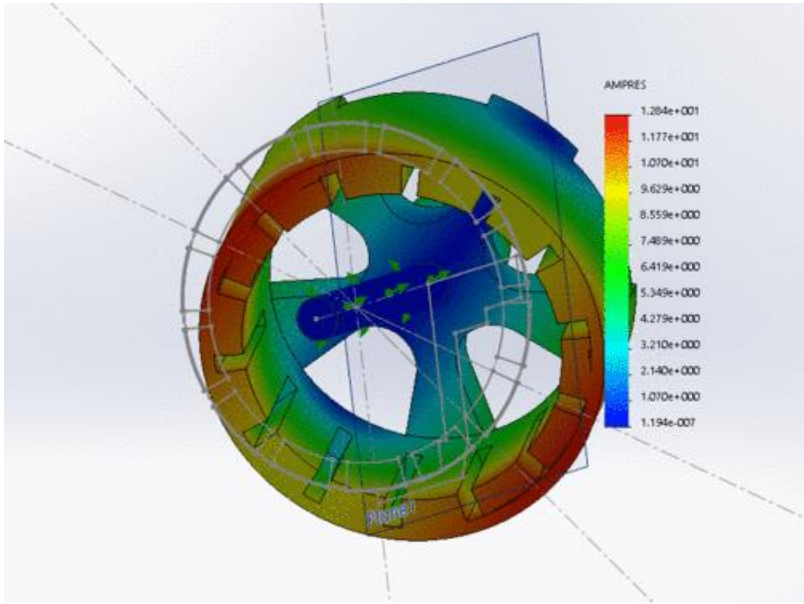
Measured



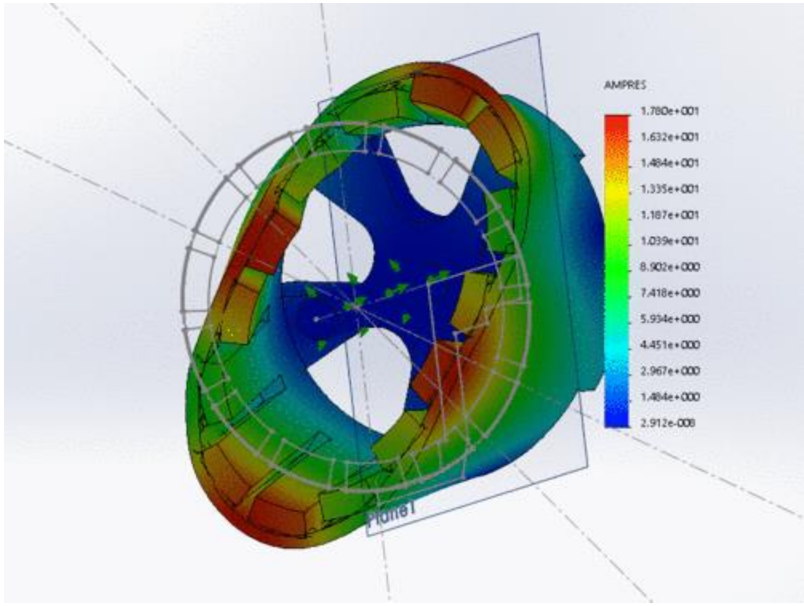


Finite Element Results

Mode 1 ~ 1.5 kHz



Mode 2 ~ 4 – 5 kHz

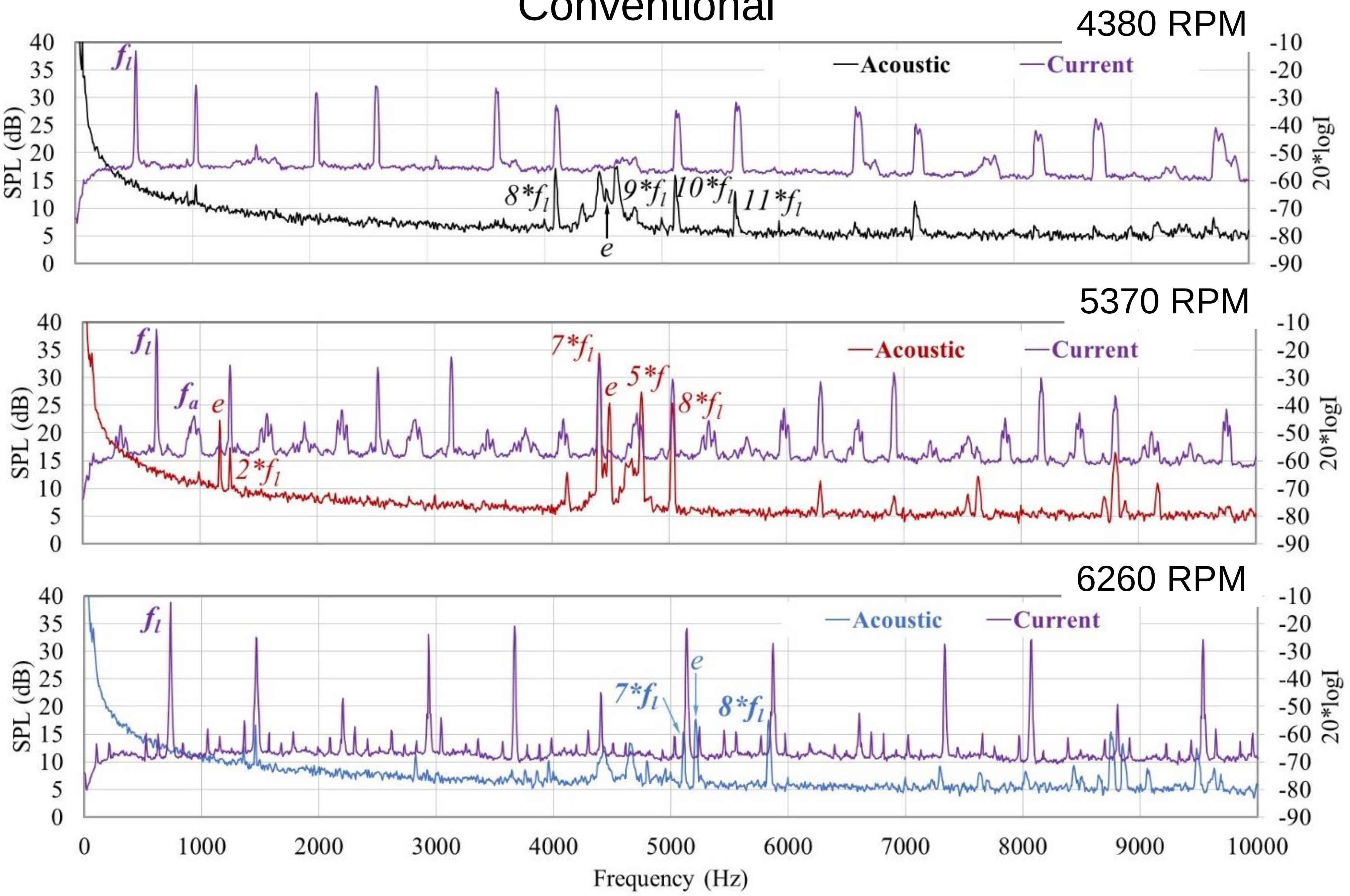


Configuration	**Frequency (Hz) Mode 1**	**Frequency (Hz) Mode 2**
Static Rotor with Adhesive	1230	5020
Static Rotor without Adhesive	1230	5270
Rotor at 4350 RPM	1390	4650
Rotor at 5370 RPM	1390	4650

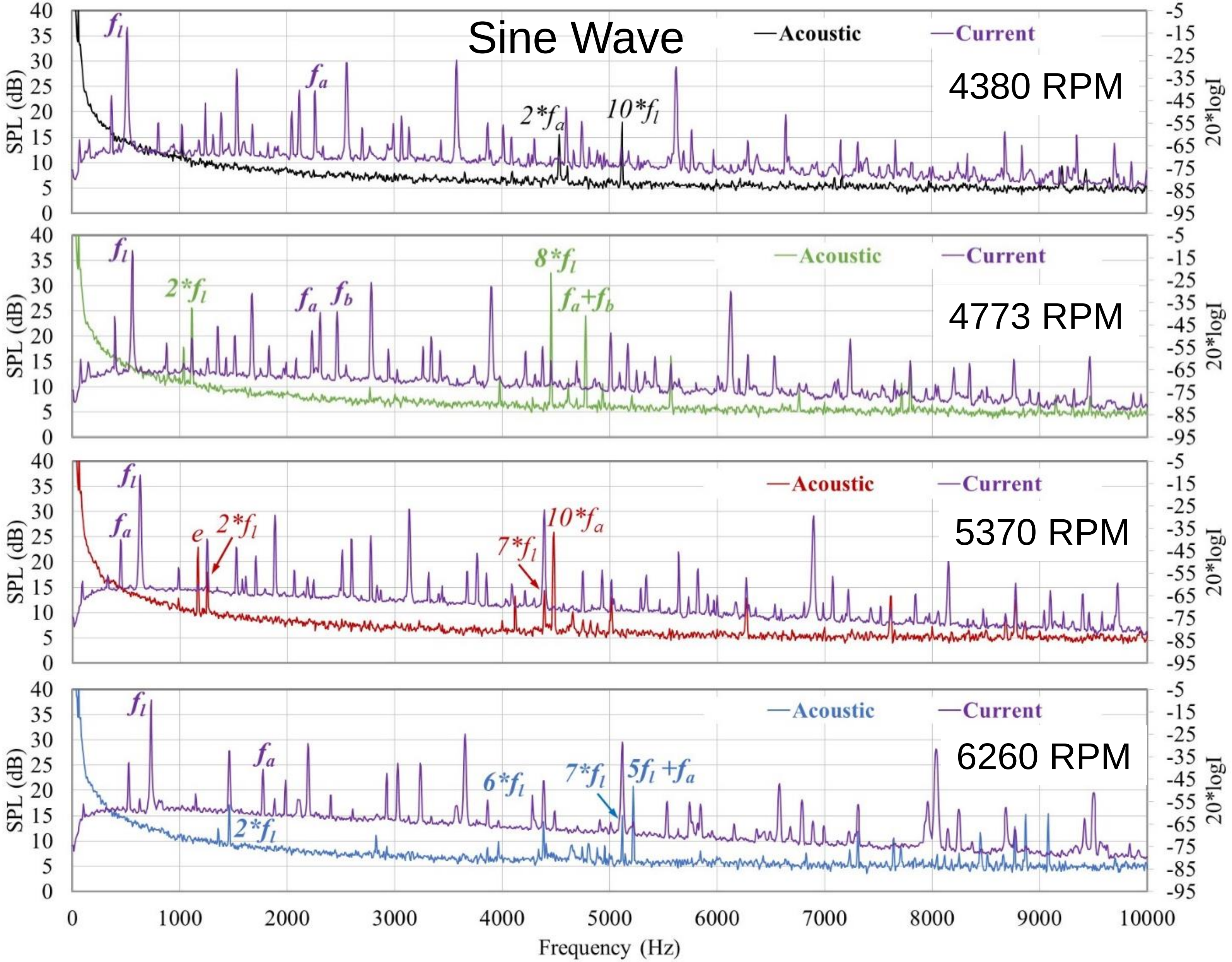
UNINSTALLED ACOUSTICS

Motor Speed Impact

Conventional

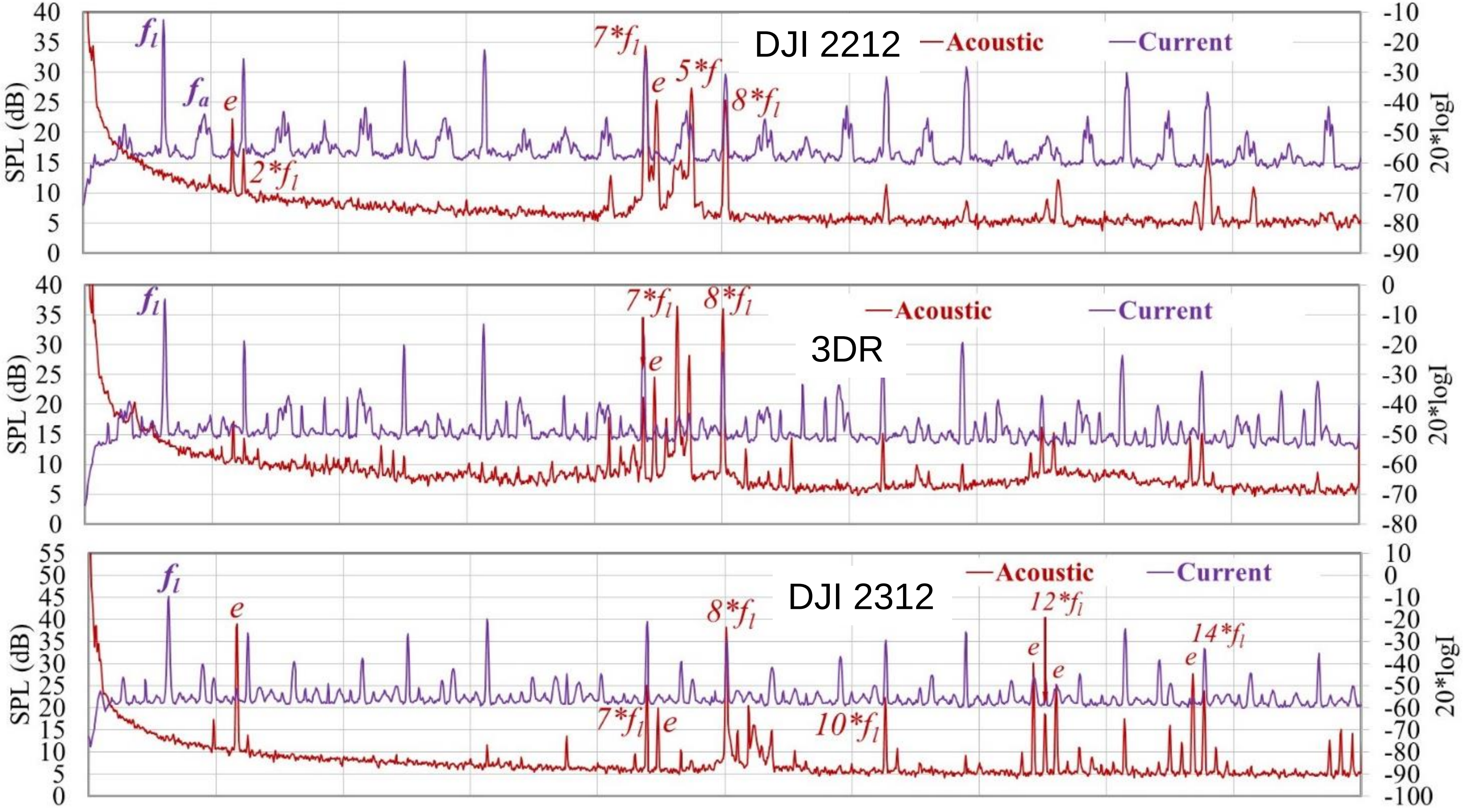


Motor Speed Impact



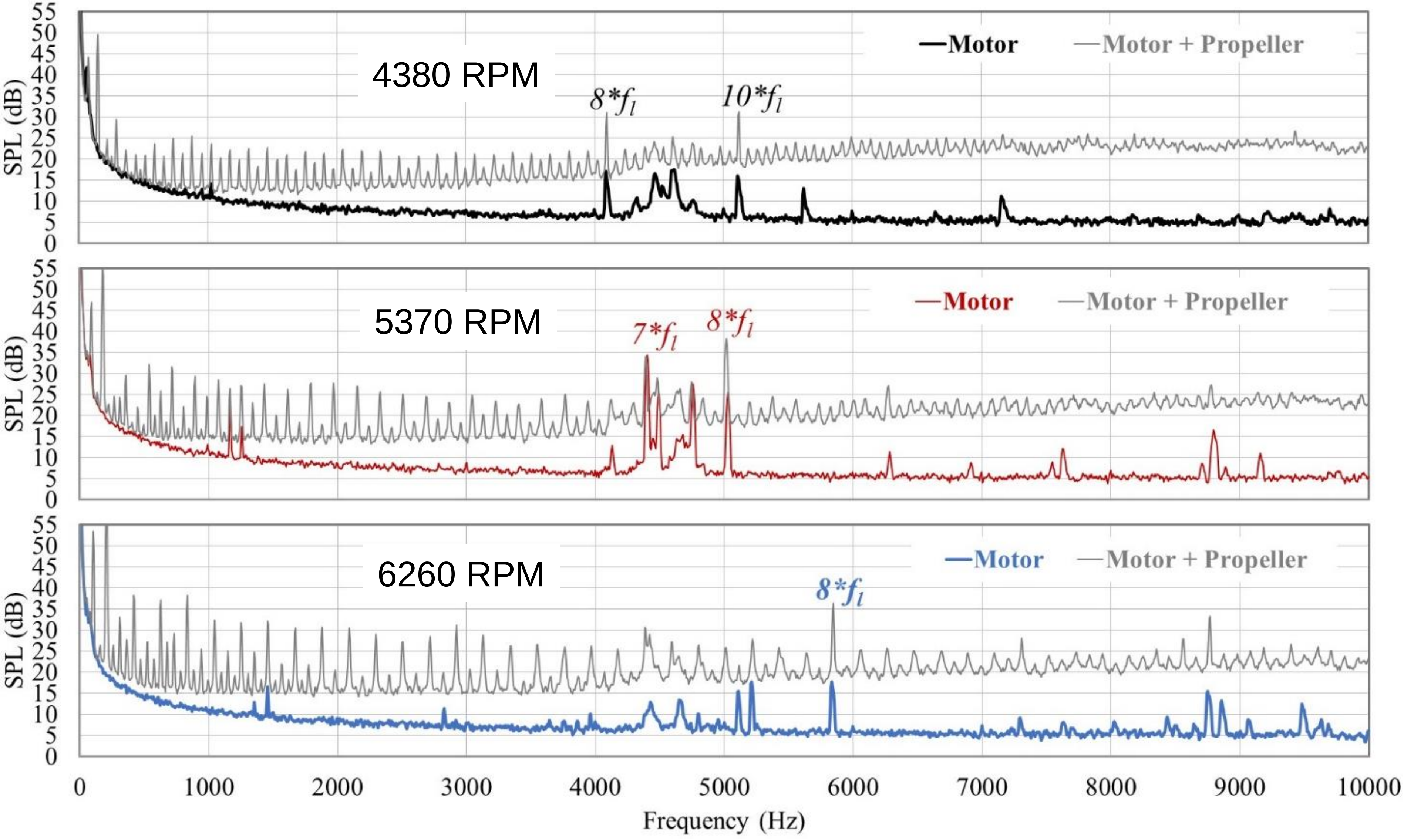
Motor Impact

Conventional

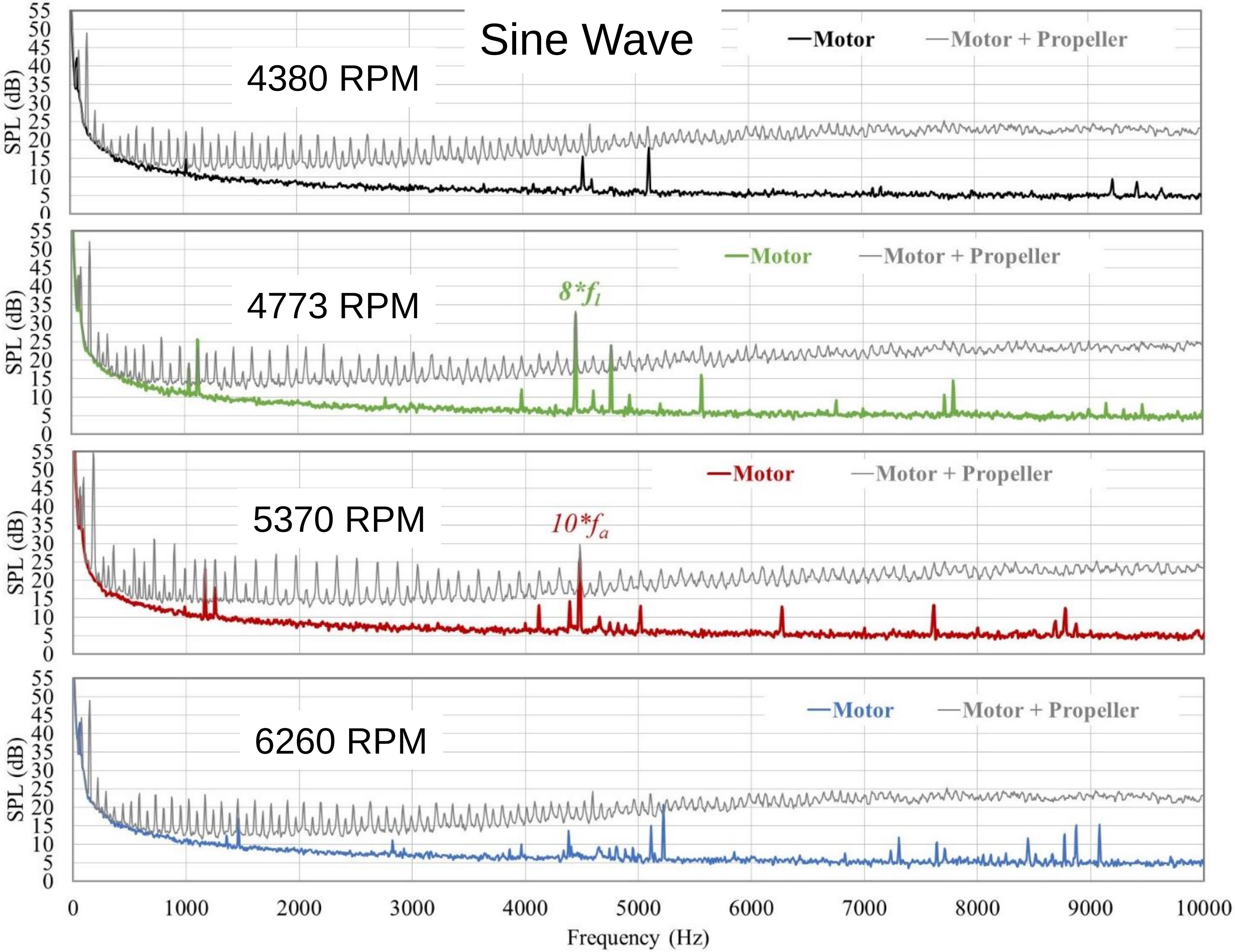


Loading Impact

Conventional



Loading Impact



Sine Wave

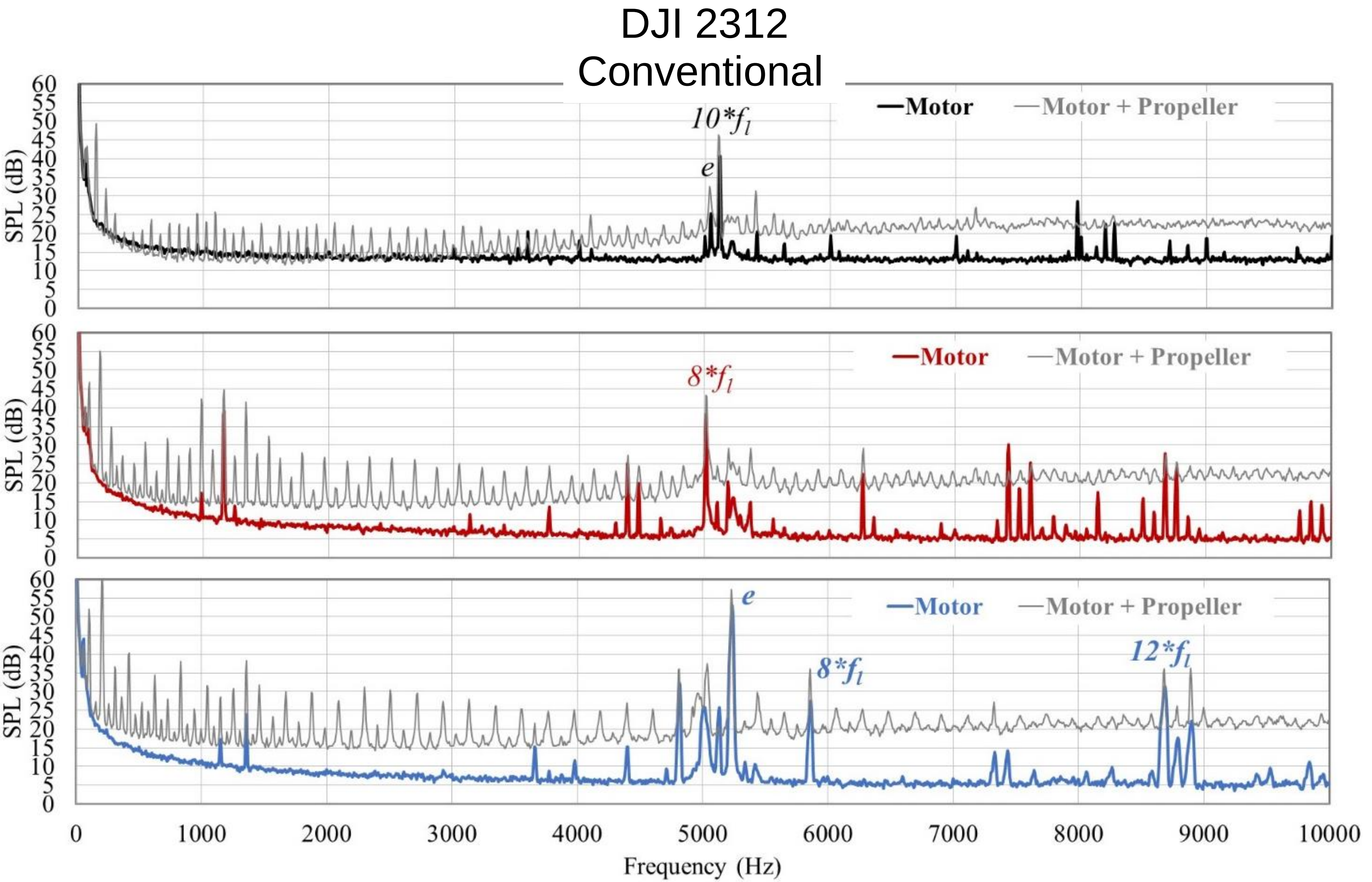
4380 RPM

4773 RPM

5370 RPM

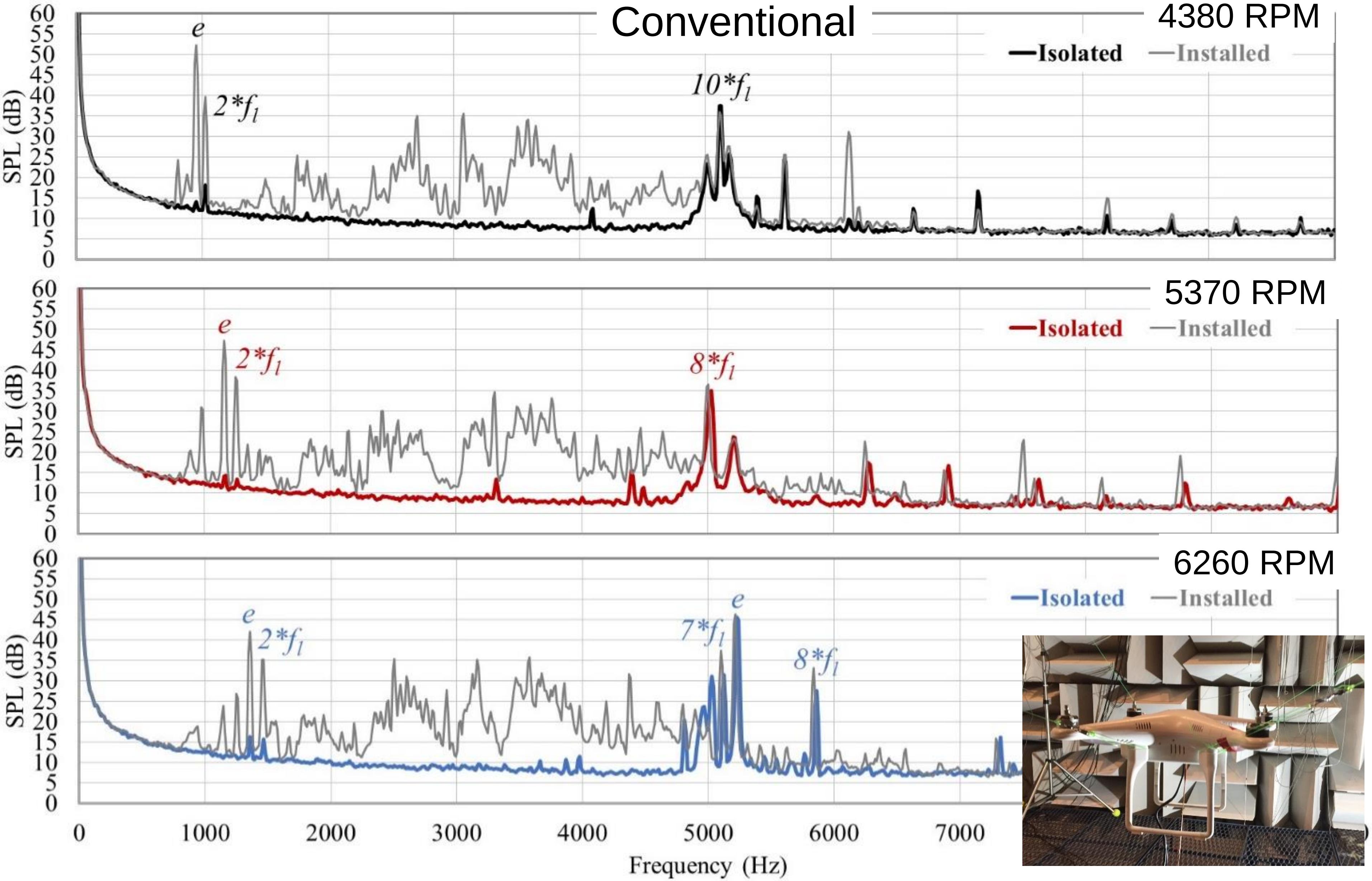
6260 RPM

Loading Impact



INSTALLED ACOUSTICS

Installed Acoustic Radiation



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