

An Initial Electric Motor Rotor Vibration Model

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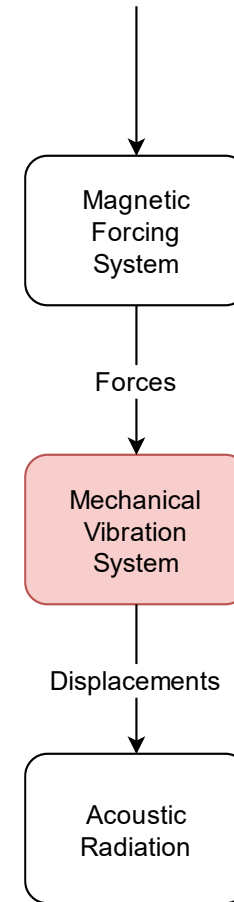
Motivation

- Need a low fidelity noise prediction tool for system level studies
- Electric motors on Urban Air Mobility (UAM) aircraft generate tones
 - Tones caused by motor resonance
 - Tones can be relevant even with propellor noise
- Building a high-level prediction tool to predict the tones generated by these motors



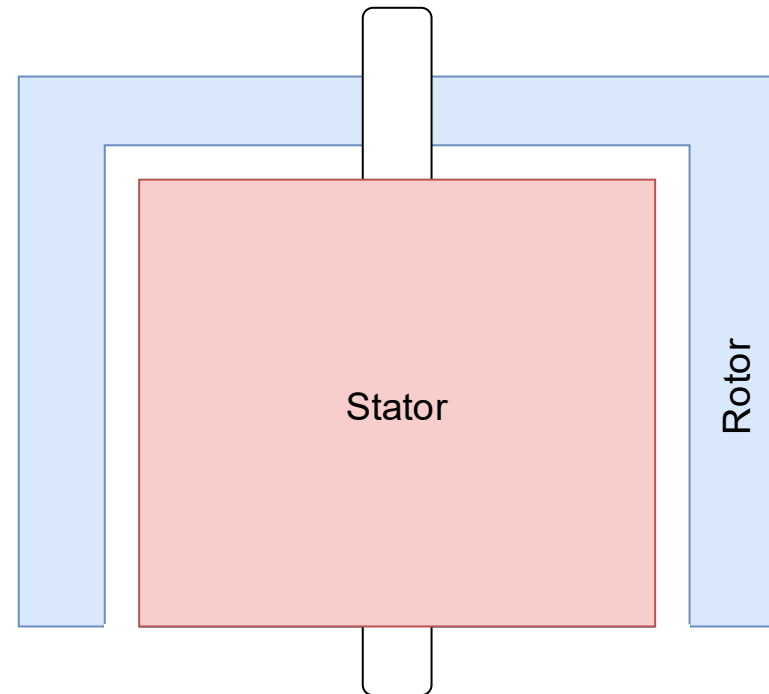
Model of Electric Motor Noise Generation

- Magnetic forcing is generated by the interaction of the stator electromagnets and the permanent magnets of the rotor
- Forcing excites vibrations of the motor rotor
- Vibrations generate sound that propagates to observers
- This work focuses on predicting the rotor Eigenmodes and Eigenfrequencies



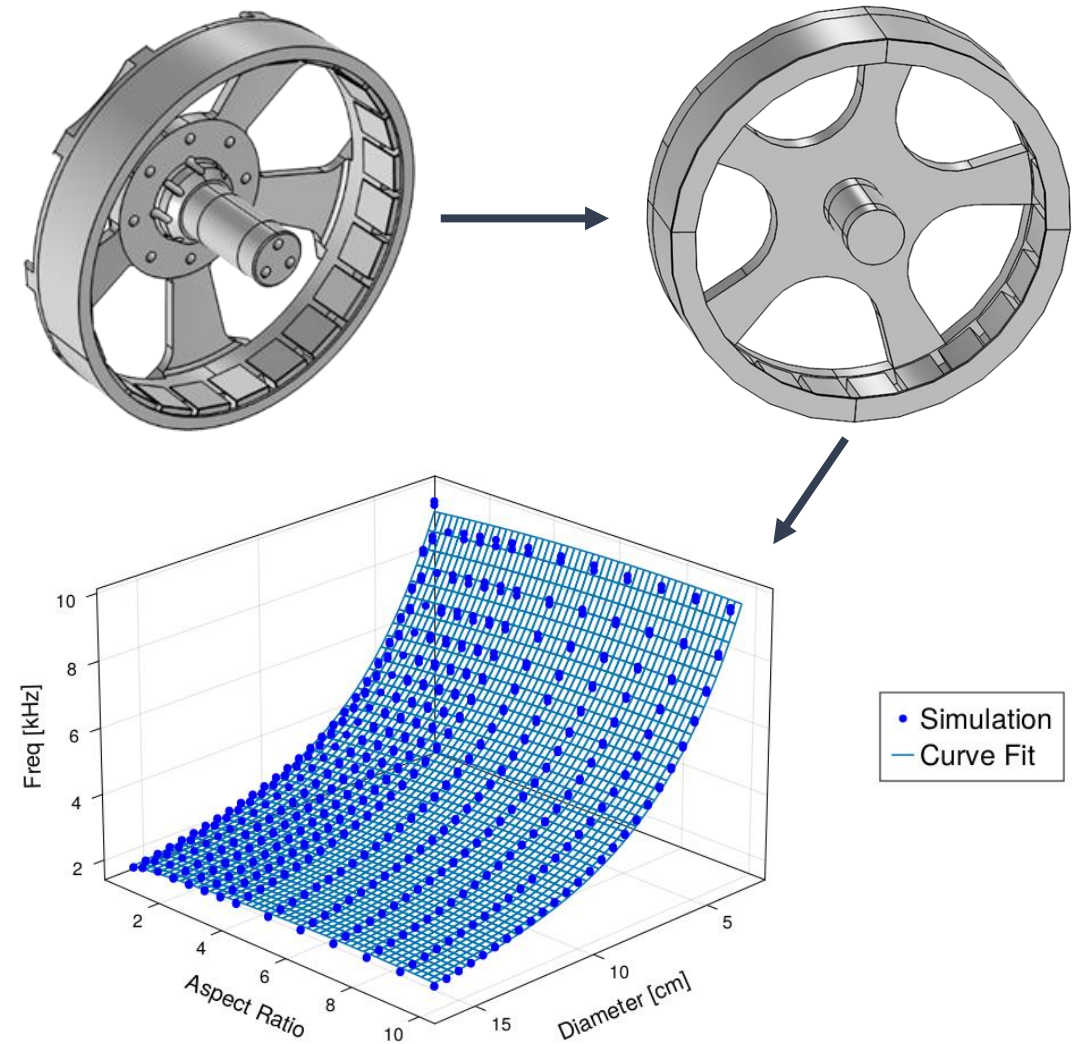
Outrunner Motor

- DC brushless electric motors
- Outer rotor surface moves and is exposed directly to the environment
- 1-5kW motor studied
 - Motors typically 2-6" in diameter
- Radial flux



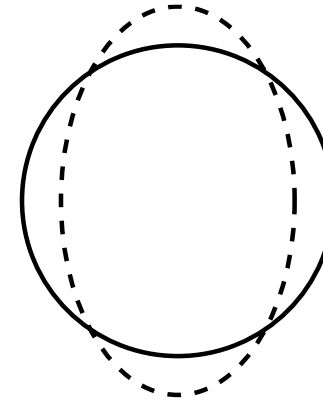
Modeling Approach

- Structure of outrunner motors requires only predicting rotor vibration modes
- Finite element models are not available for system level studies
- Use FEA to generate a low-fidelity model to predict Eigenmode shapes and frequencies of outrunner rotors
 - We expect motor acoustic to be important relative to other sources at the resonant modes of the motor
- Three stages of simulation and modeling
 - High-fidelity geometry simulations
 - Parameterized geometry simulations
 - Parameter sweep and curve fit

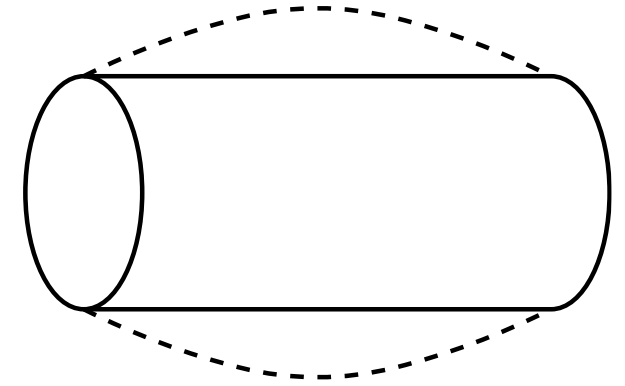


Mode Shapes

- In ideal cylinders, Eigenmode shapes can be described by azimuthal (M) and axial (N) mode numbers
- Azimuthal mode number describes the wave number in the circumferential direction
- Axial mode number is analogous to mode numbers of simple beams

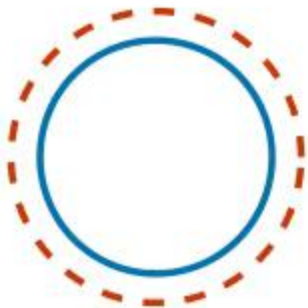


Azimuthal Mode
Number M

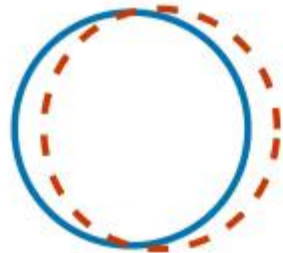


Axial Mode
Number N

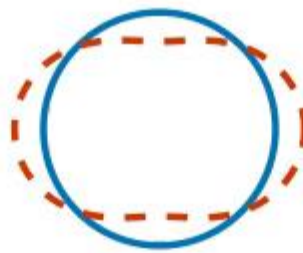
M = 0



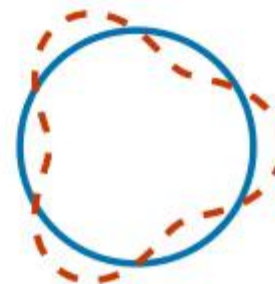
M = 1



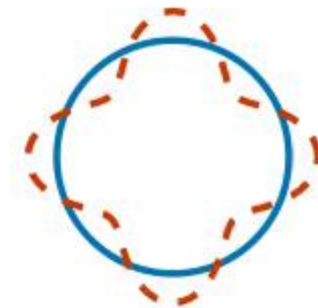
M = 2



M = 3

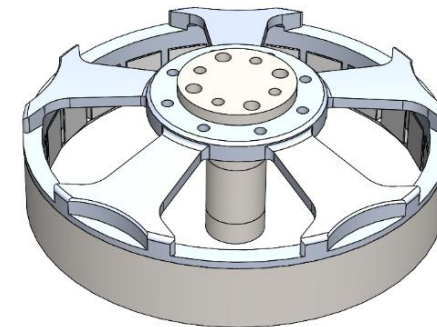


M = 4



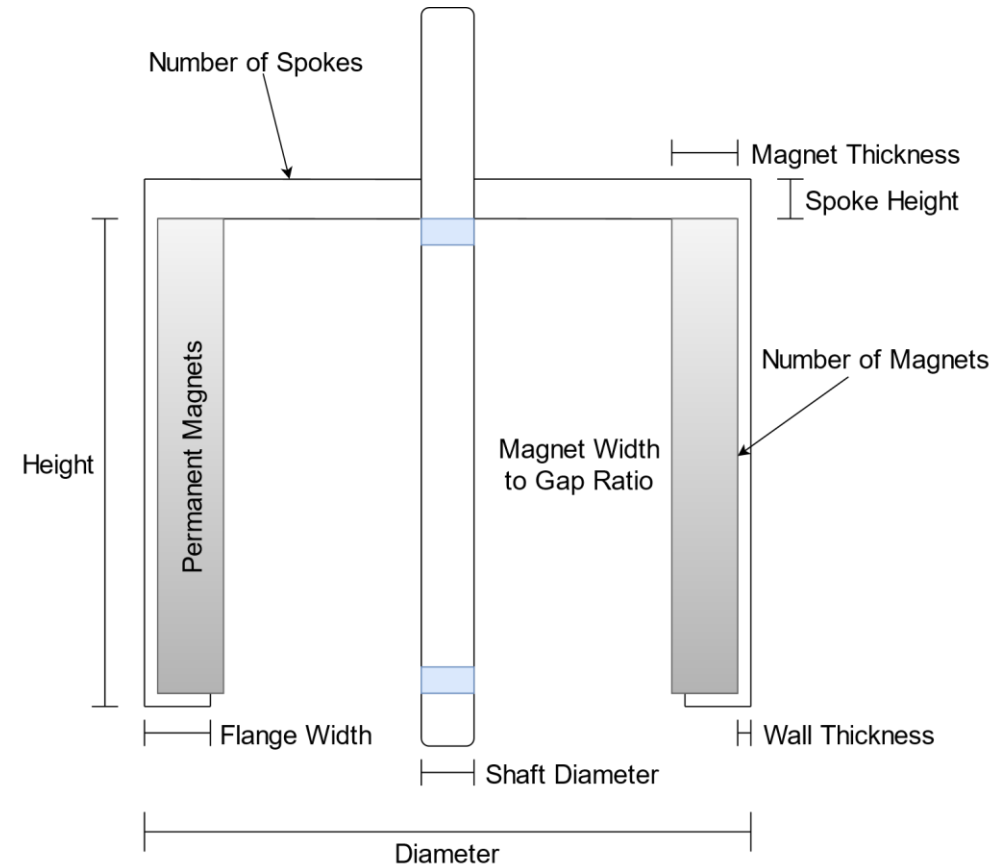
High Fidelity Model

- High fidelity geometry model created for two motors
 - Scorpion SII-4020
 - T-Motor U13 (shown right)
- Geometry represents individual parts and materials and aims to replicate as built hardware



Parameterized Model Geometry

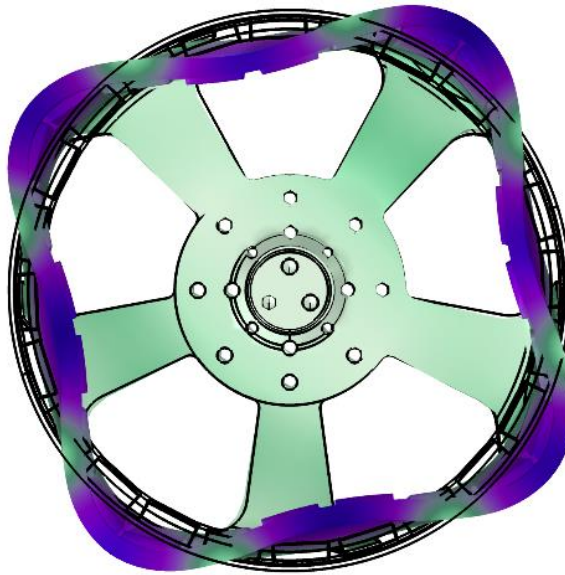
- A representative geometry was developed to capture the key geometric features that impact the eigenmodes and frequencies of the rotors
- 10 key dimensions (right) fully define a representative geometry
- Tuned to match both experiments and high-fidelity models



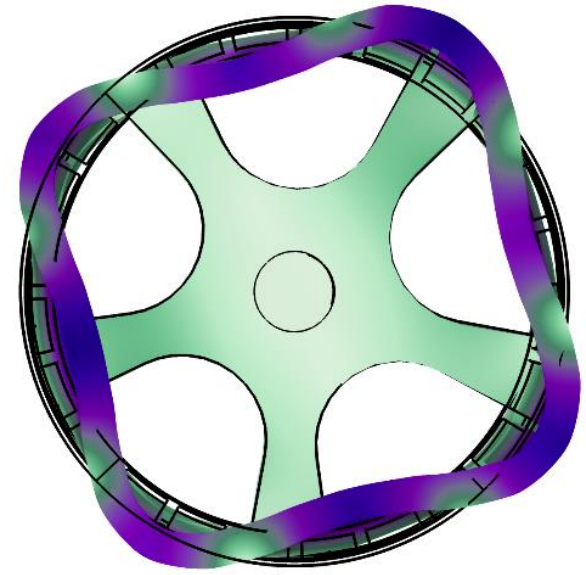
Qualitative Displacement Comparison

- Mode (4,1) rotor displacements
- Qualitative comparison of mode shapes between high fidelity and parameterized geometries shows good agreement

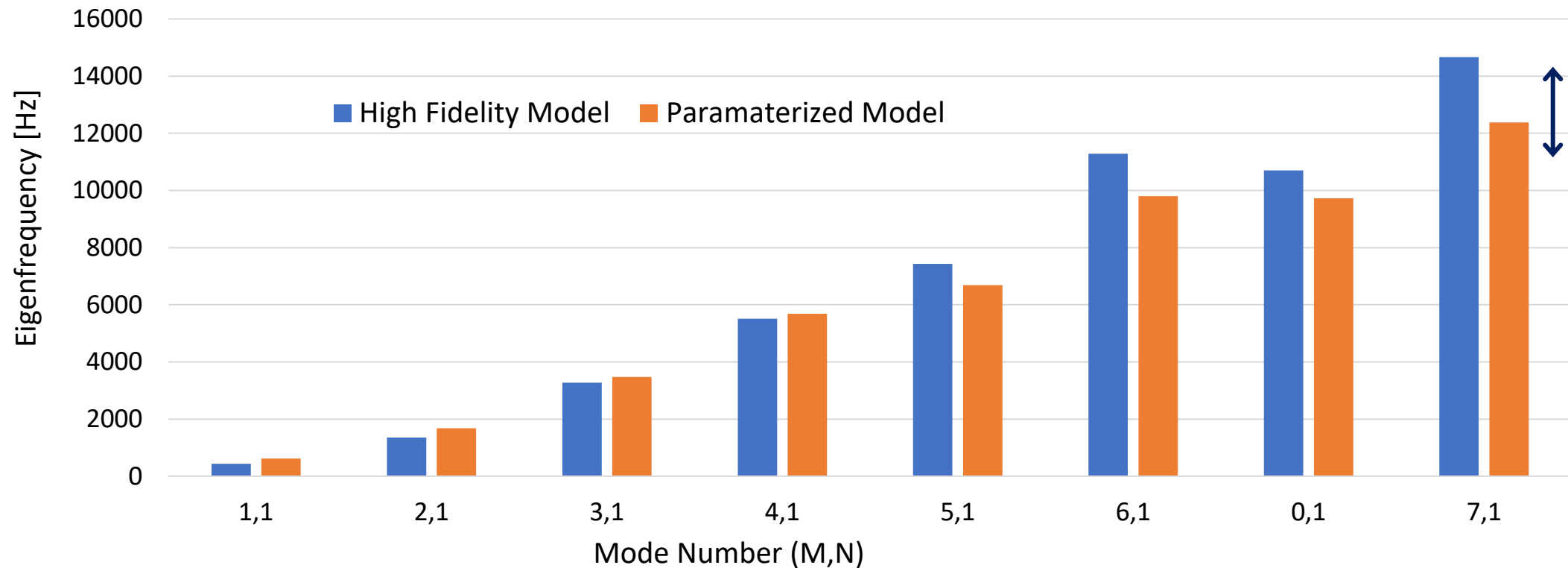
High Fidelity 5513 Hz



Parameterized 5685 Hz



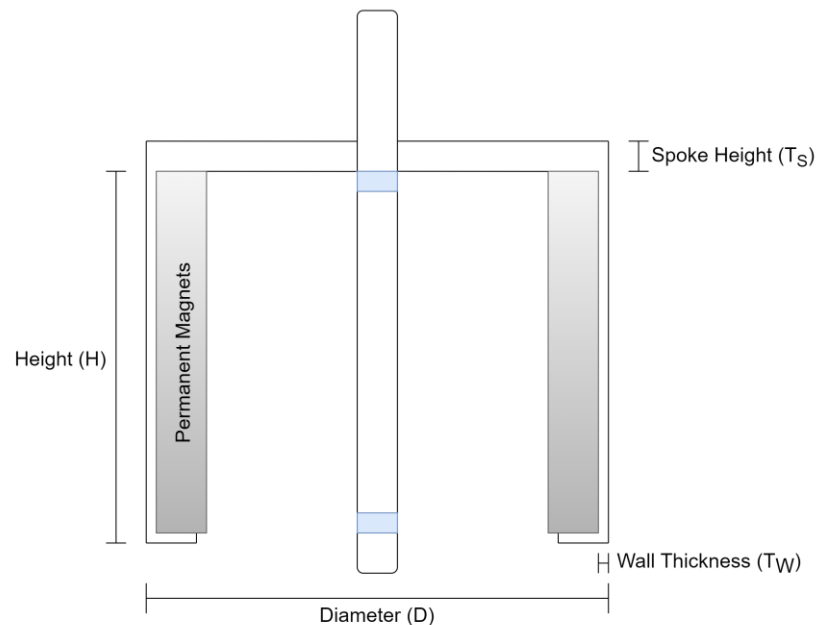
Eigenfrequency Prediction Comparison



Good agreement (within 1/3rd octave band for ANOPP2) for the qualitatively identifiable mode shapes.

Parameter Sweep

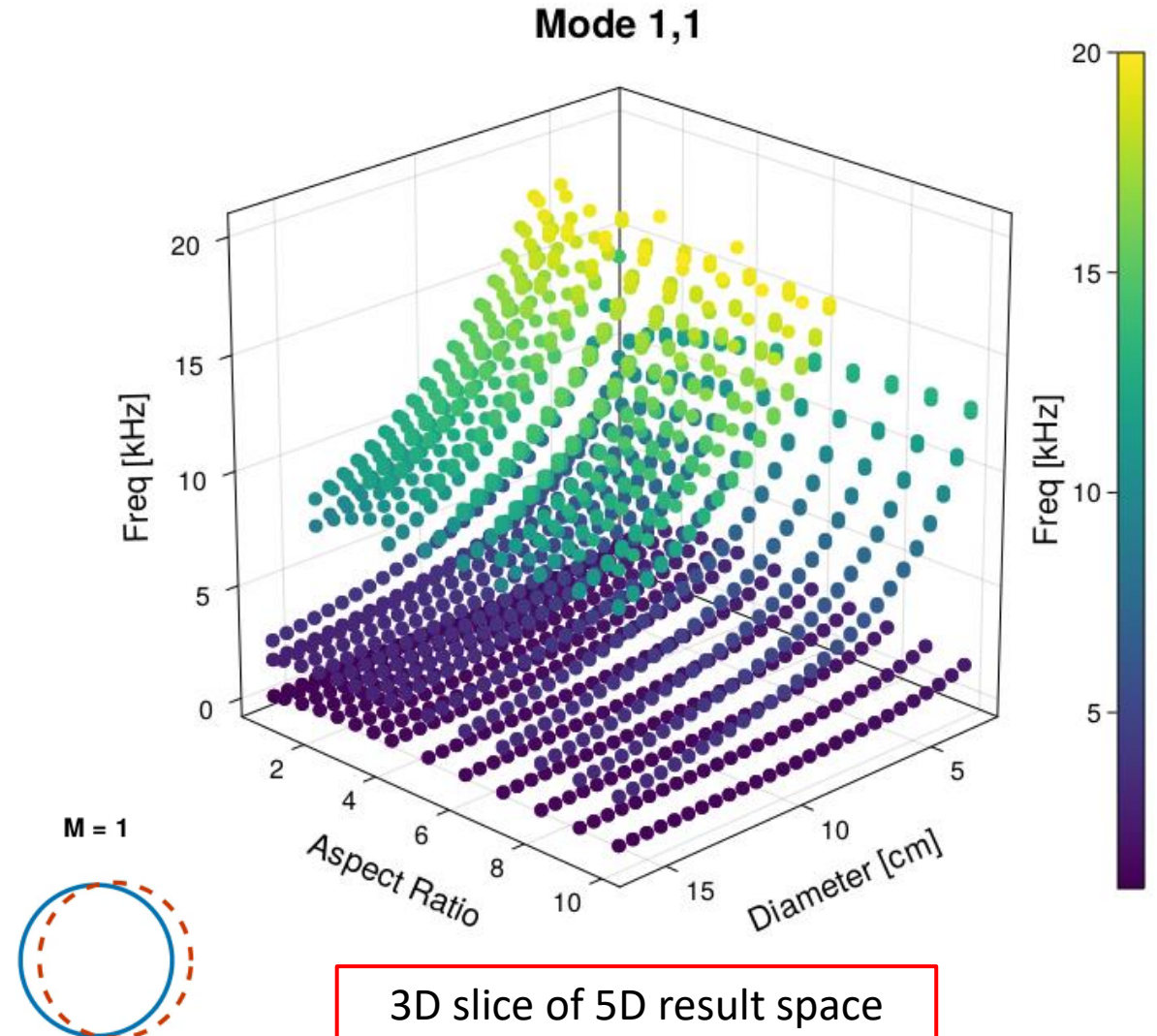
	Minimum	Maximum	Interval	Number of Samples
Rotor Diameter (D)	30mm	160mm	5mm	27
Aspect Ratio (D/H)	0.7	10	Variable	14
Wall Thickness Ratio (T_w/D)	0.02	0.04	0.01	3
Spoke Height Ratio (T_s/H)	0.1	0.3	0.1	3



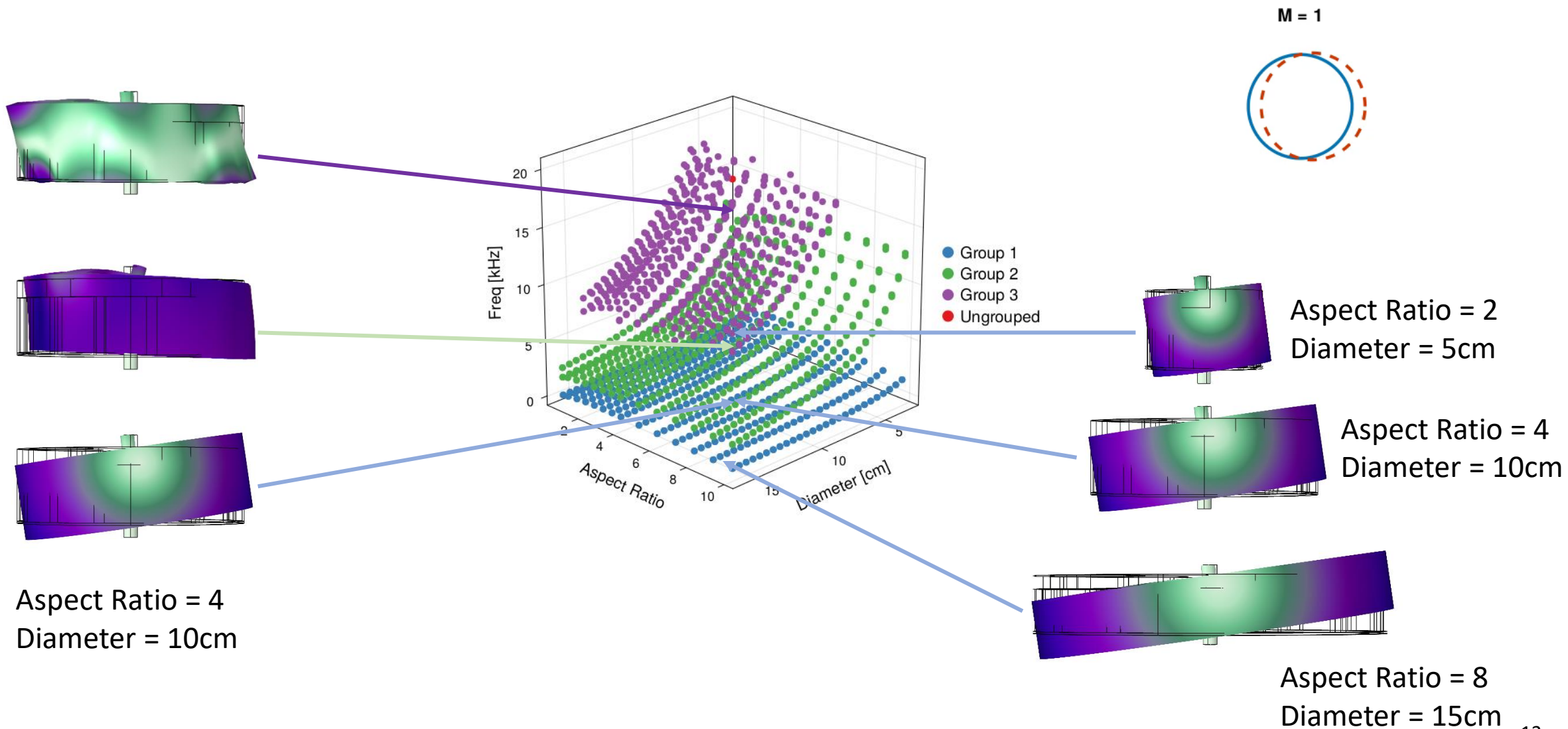
- 4 of the 10 key parameters were selected to be varied
- Studied range reflects the variation in studied real world motors
- ~3400 total combinations
- Mode shape (M,N) for each result identified by 2D spatial FFT of rotor surface displacement

Parametric Sweep Results

- 3400+ simulations
 - 35 results per simulation
 - Each result has M,N and frequency
- Dimensions not shown
 - Spoke height
 - Wall thickness
 - Other modes
- Three distinct groups are visible
 - Each group same mode shape
 - Differences in details of vibration

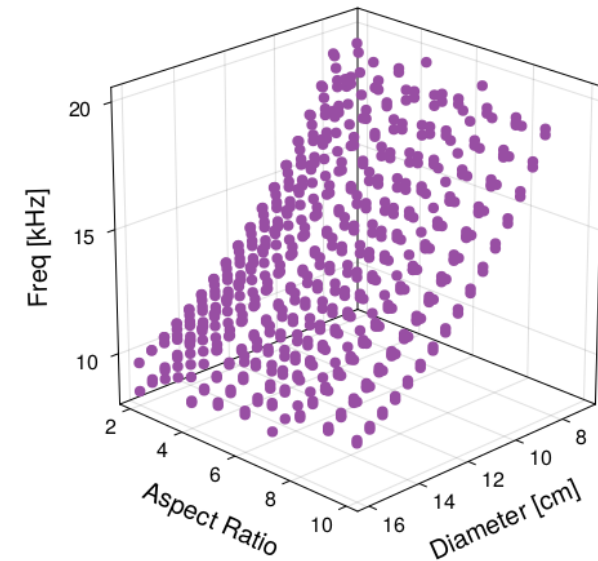
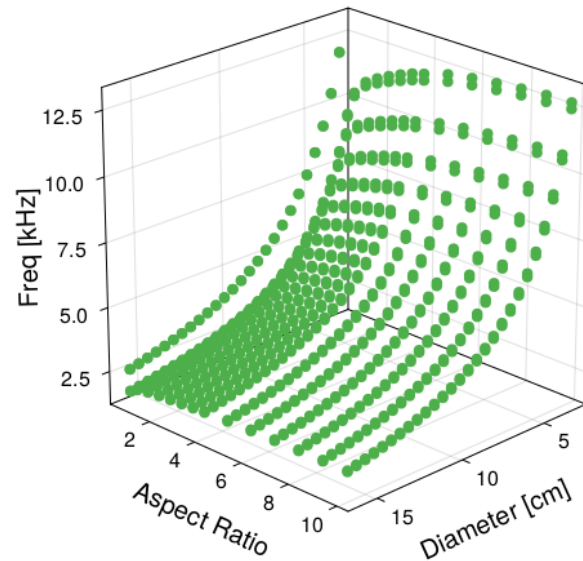
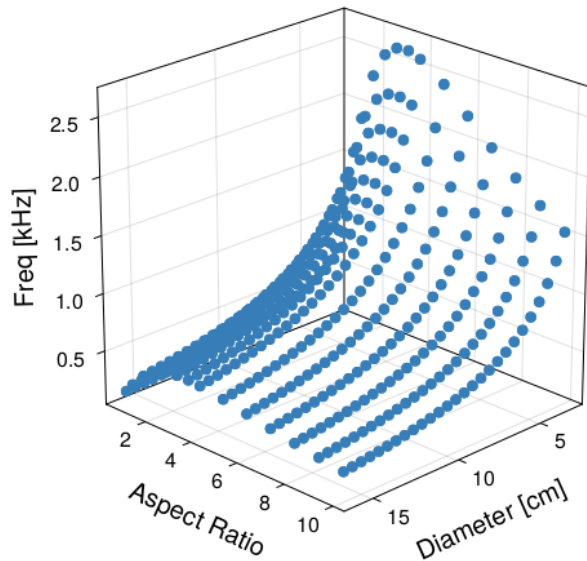


Mode (1,1) Shape Comparison

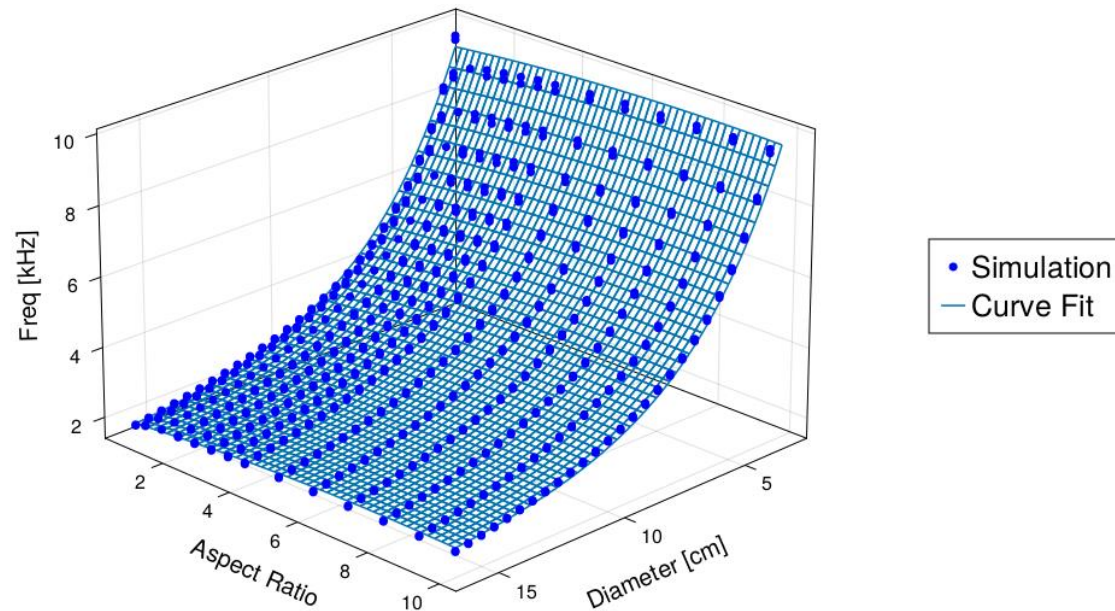


Individual (1,1) Groups

- The groups are separated using DBSCAN clustering
- 3 groups below are the assigned groups from the (1,1) collection datapoints
 - Each group shown here is only 3D slice
 - Each group spans the 5D parameter space



Curve Fit For Group 2

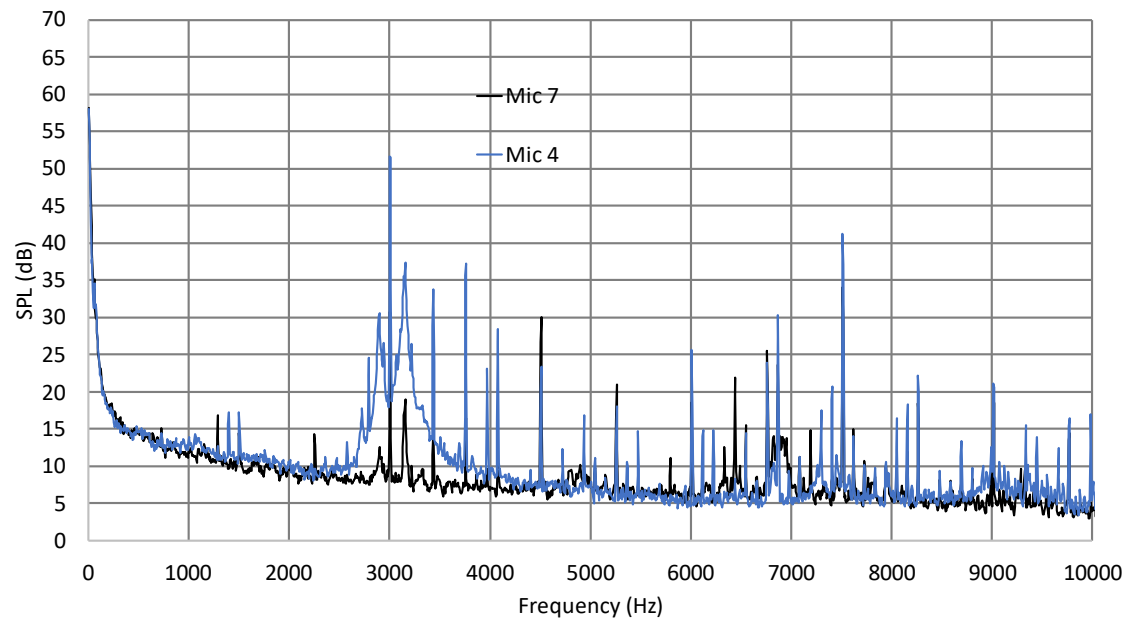
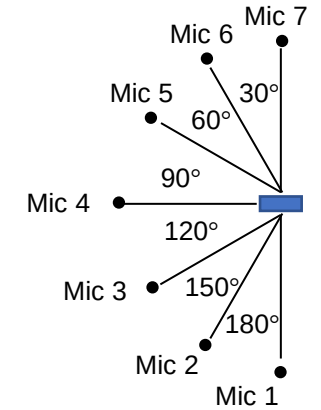


3D slice of 5D result space

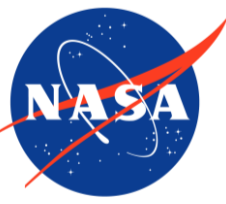
- Separate fit and limits have been set for each individual group for each mode shape (M,N) combination
- Curve fit details are provided in the paper

Experimental Validation - Scorpion

Mode Shape	FEA Frequency (Hz)	Experimental Frequency (Hz)	Percent Error
1,1	895	799	12.0
2,1	3120	2961	5.4
3,1	7070	6914	2.3
0,1	22460	24379	7.87



- High fidelity FEA prediction at 3.1 kHz (2,1) mode
- Experimental modal analysis mode detected at 3.0 kHz, (2,1) mode
- Acoustic tone near 3 kHz



Conclusion

- For a low fidelity prediction, the resonant Eigenmodes and Eigenfrequencies can be predicted using a curve fit with 4 key motor parameters. This is a suitable tool for system level studies such as in ANOPP2
- The present model applies to a limited set of motors
 - Outrunner
 - 1-5kw
 - Brushless DC
 - Radial Flux

Questions?

