Experimental and Numerical Investigation of Propeller-Propeller Dynamic Interaction in a DEP System

Tanuj Sharma, PhD researcher

Supervisors: Dr. Djamel Rezgui, Dr. Branislav Titurus

A little about me

- *International Student* – New Delhi, India.
- *MEng Aerospace Engineering*, 2017-2021, University of Bristol.
- *PhD* (2021) – University of Bristol.
- Research Associate (Jun 2025) – University of Bristol
- Supervisors: Dr. Djamel Rezgui, Dr. Branislav Titurus

Contents

Introduction to UAM

- Transform urban transportation by integrating electric vertical take-off and landing (eVTOL) aircraft.
- Aim to reduce congestion and improve transportation efficiency.
- Can offer environmental sustainability
- **Multirotor** concepts with **tilting capabilities**
- Can lead to new **complex dynamics**

Vertical Aerospace VX4 [1]

Joby S4 [2]

1. https://evtol.news/vertical-aerospace-VA-1X
2. https://aviationweek.com/aerospace/advanced-air-mobility/joby-building-first-certification-test-s4-evtol

Challenges in eVTOL Dynamics

Vibration Behaviour
- Identifying and Avoiding Resonance
- Mitigating Vibrational Impacts

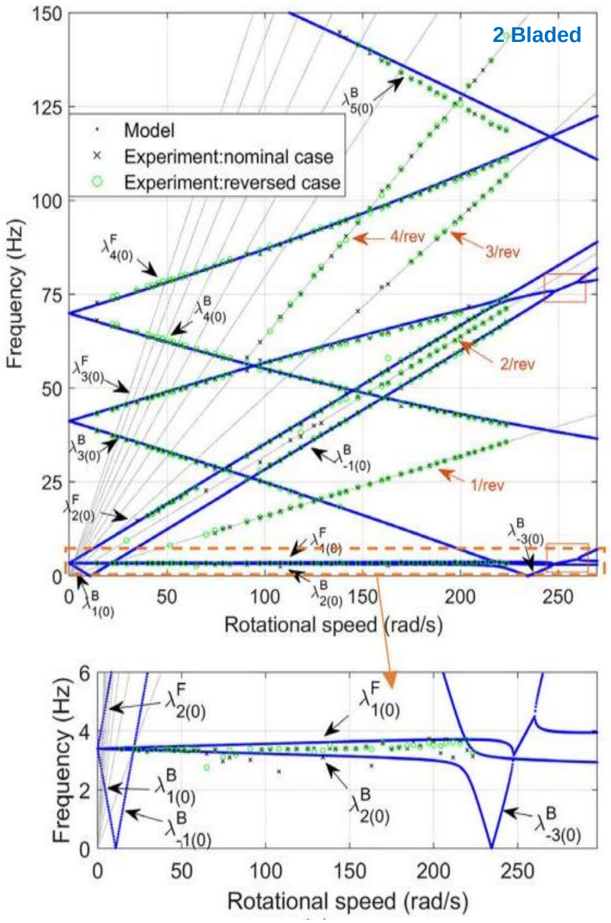
Dynamic Stability
- Whirl Flutter
- Stability of Articulated Tilting Rotor System

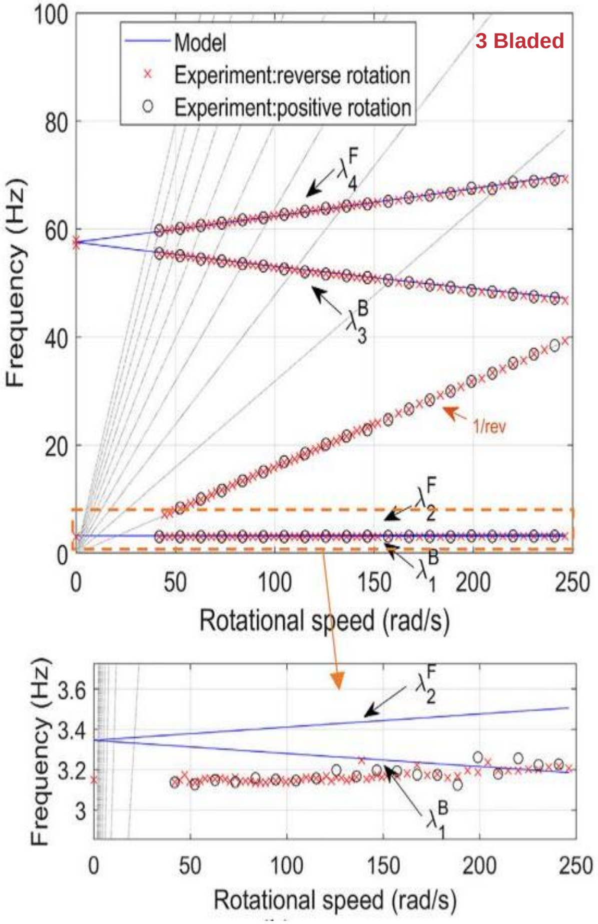
Complex Interactions
- Rotor-Structure Interaction ✔
- Rotor-Rotor Interaction

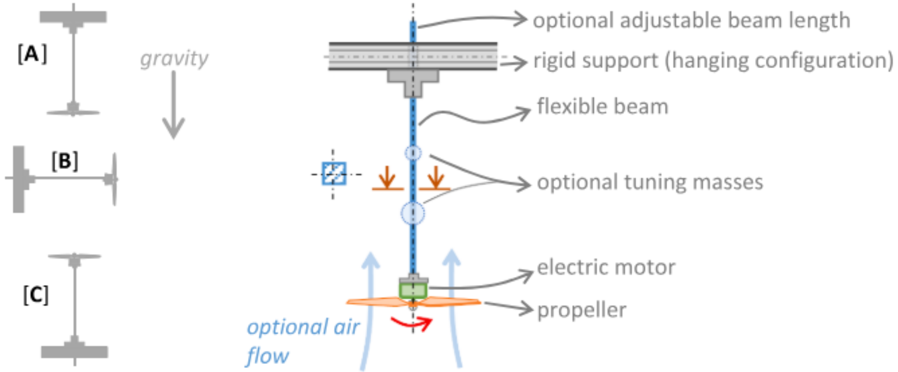
Need for Comprehensive Research:

- Addressing these challenges necessitates the development of specialised experimental rigs.
- Accurate emulation of full-scale eVTOL dynamics is essential for controlled investigations.

Complex Dynamic Interactions







Research Aim & Objectives

Aim

To investigate the influence of rotor spacing and speed variation on mode veering, forward/backward whirling, and resonance interactions in a multirotor configuration using a validated experimental rig and numerical model.

Objectives

1. **Dual-Rotor Test Configuration**
   - Use a validated tilting multirotor rig equipped with two independently driven rotors and variable spacing.
2. **Numerical Interaction Modelling**
   - Extend a 1D MSC NASTRAN beam model to capture gyroscopic, Coriolis, and inertial coupling effects.
3. **Experimental Modal Analysis**
   - Conduct shaker tests, extract FRFs, natural frequencies, damping ratios, and mode shapes.
4. **Numerical–Experimental Validation**
   - Compare modal trends and Campbell diagrams to evaluate rotor–rotor interaction.

Dynamic Scaling Methodology

1. Necessity of Dynamic Scaling
   - **Accurate Representation**: Vibrational and Stability characteristics of eVTOL aircraft.
   - **Practicality**: Size, Cost, and Complexity.
2. Objective of Scaling
   - Ensure the rig reflects the same dynamic behaviour as the full-scale eVTOL aircraft.
   - Dynamically Scale Maxwell X-57 eVTOL aircraft characteristics.
3. Scaling Approach
   - Ensure the order of modes is preserved → **OP1/IP1/OP2/T1**.
   - Target frequency ratios to align with the Maxwell X-57's full-scale ratios of **[1, 3.24, 6.36, 7.67]**.
   - Frequencies (9-100 Hz) <→ RPM Range (450-6000 RPM).

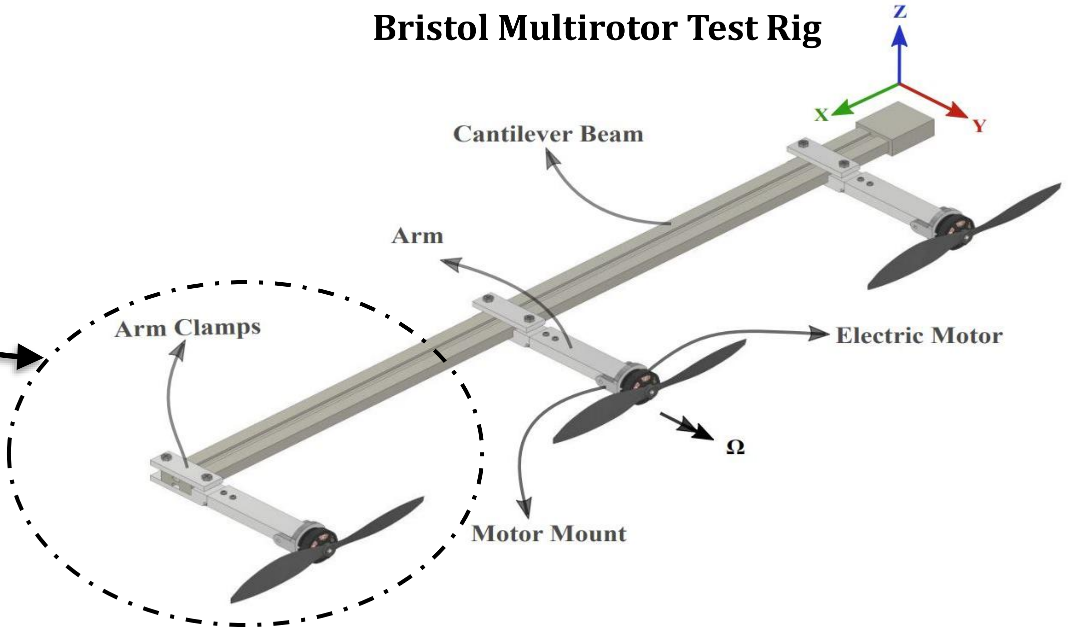
Maxwell X-57 [1]

1. https://www.nasa.gov/centers-and-facilities/armstrong/x-57-maxwell/

Preceding Research: *Multirotor Test Rig & Numerical Validation*

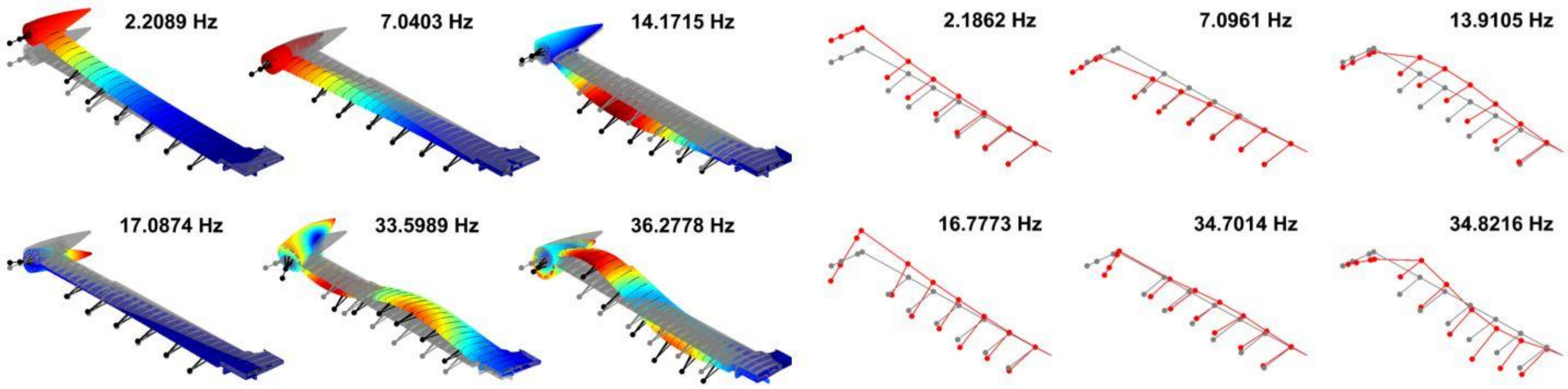
- **Dynamically scaled multirotor test rig**
  - ✓ Developed to match modal characteristics of NASA X-57 (via SQP-based Optimisation).
  - ✓ Dynamic Characterisation → 1 Rotor Case
- **Validated numerical models (1 Rotor)**:
  - ✓ 3D solid model for structural fidelity.
  - ✓ 1D NASTRAN beam model with gyroscopic effects.
- **Experimental setup**:
  - ✓ Impact hammer tests with 5 accelerometers (OP, IP, torsion, pitch, yaw).
  - ✓ Test Matrix: 0–4500 RPM.

Bristol Multirotor Test Rig



Mode	Optimisation [Hz]	NASTRAN [Hz]	Experiment [Hz]	Experiment Damping (%)
1^{st} Bending	10.45	10.38 (0.67%)	10.23 (2.13%)	0.60
1^{st} In-Plane	32.11	32.92 (2.49%)	31.66 (1.43%)	0.26
2^{nd} Bending	62.88	63.36 (0.76%)	64.07 (1.87%)	0.07
1^{st} Torsion	78.58	70.32 (11.10%)	76.21 (3.06%)	0.25

NASA Maxwell X-57 – FEM Results

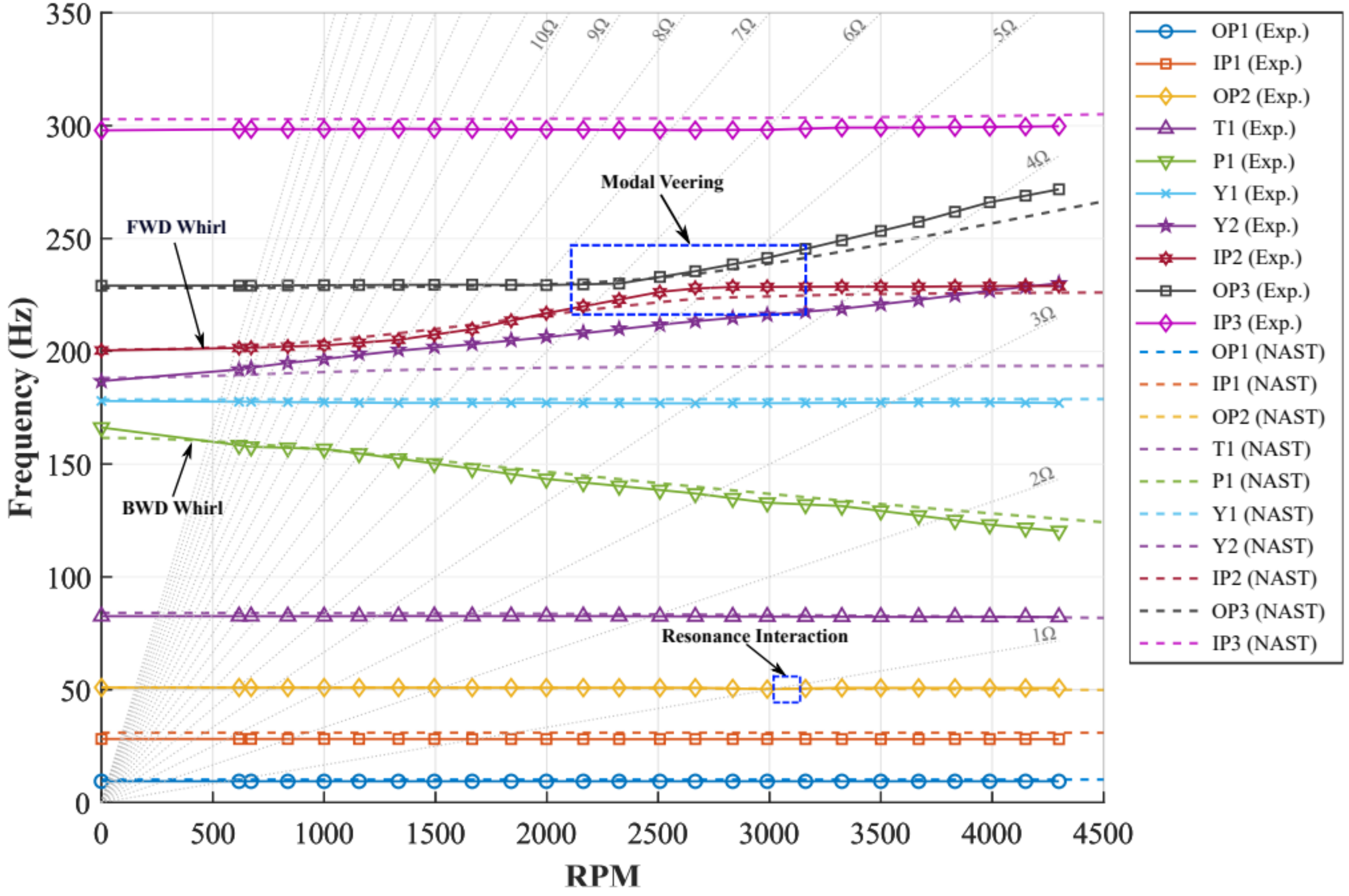


(a) Full FEM (b) Beam model

Modes	Full FEM	Beam Model
1st Bending	1.00	1.00
1st In-Plane	3.18	3.24
2nd Bending	6.42	6.36
1st Torsion	7.70	7.67

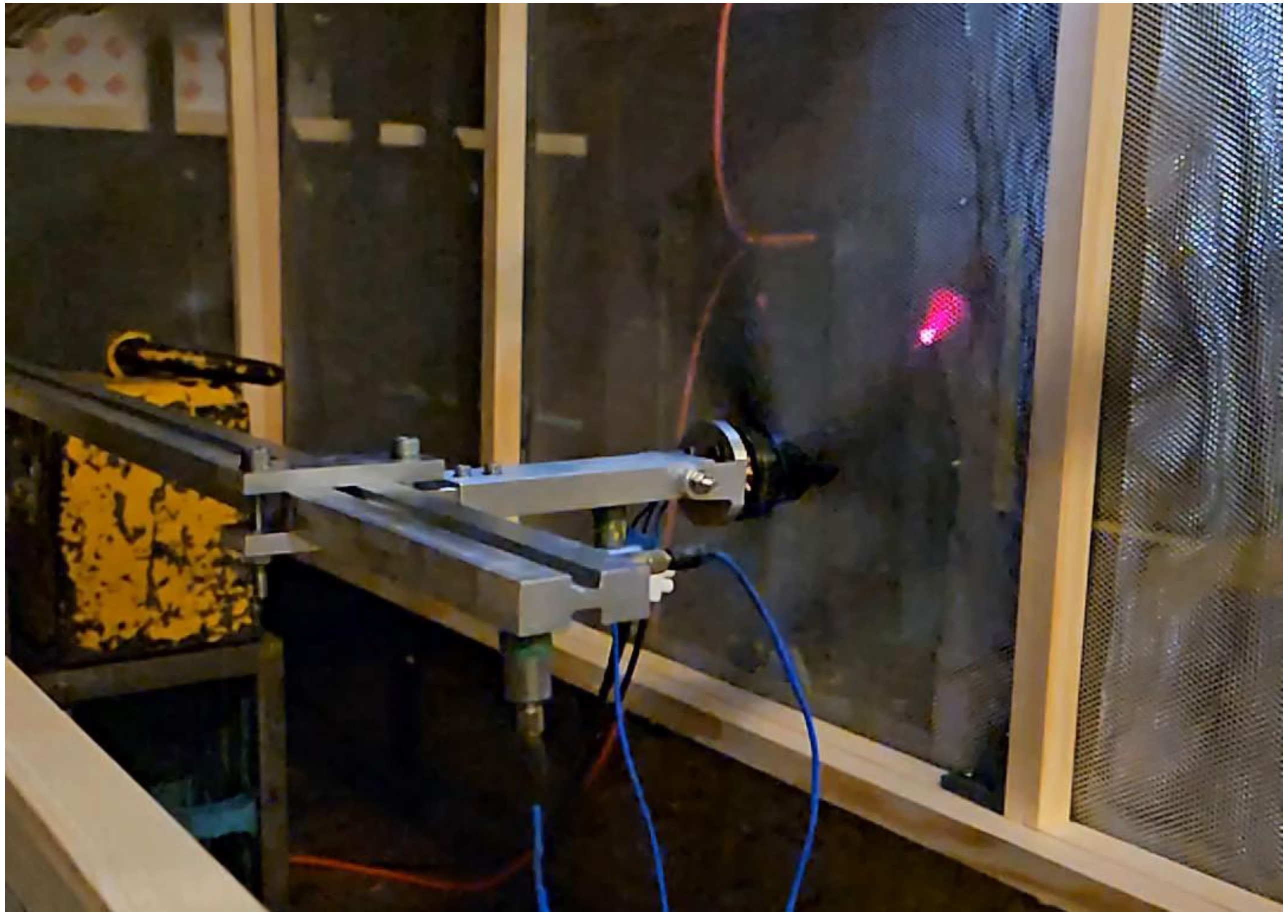
Hoover, C.B., Shen, J., Kreshock, A.R., Stanford, B., Piatak, D.J. and Heeg, J., 2017. Whirl flutter stability and its influence on the design of the distributed electric propeller aircraft X-57. In *17th AIAA Aviation Technology, Integration, and Operations Conference* (p. 3785).

Preceding Research: *Key Phenomena and Outcomes*



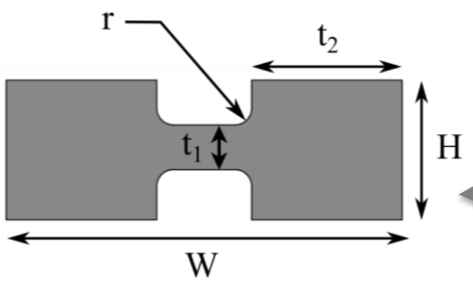
- Captured fundamental dynamic effects:
  - ✓ **Mode veering**
  - ✓ **Forward/backward whirl**
  - ✓ **Resonance interactions**
- **Strong agreement** between numerical and experimental modal properties (<4% error typical).
- Test rig demonstrated sensitivity to rotor RPM, suitable for controlled exploration of coupled dynamics.

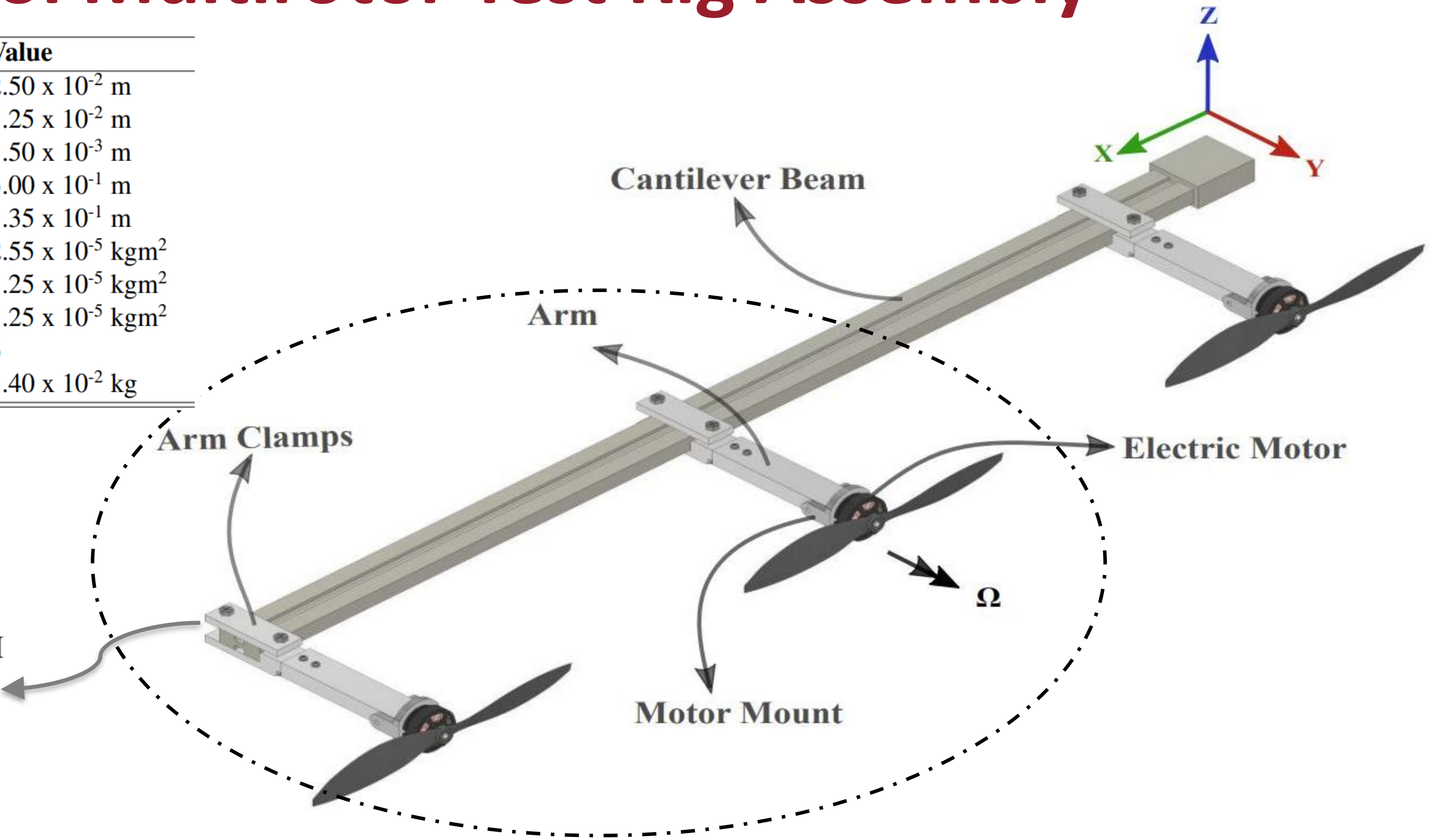
Preceding Research: *Resonance Interaction at 3150 RPM*



Bristol Multirotor Test Rig Assembly

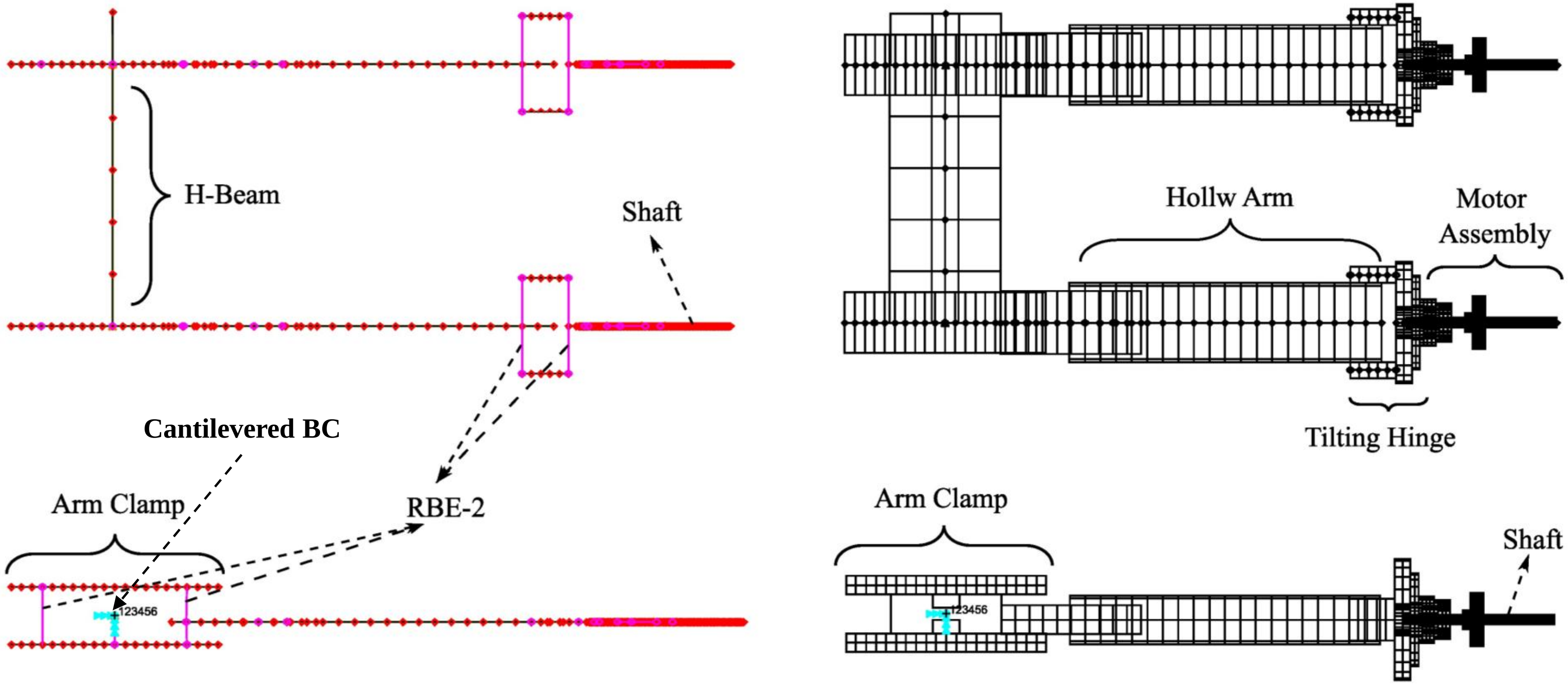
Parameter	Value	Parameter	Value
W	3.55×10^{-2} m	b_{arm}	2.50×10^{-2} m
H	1.25×10^{-2} m	h_{arm}	1.25×10^{-2} m
t_1	4.00×10^{-3} m	t_{arm}	1.50×10^{-3} m
t_2	1.35×10^{-2} m	m_{arm}	3.00×10^{-1} m
m_e	1.00×10^{-1} kg.m	L_{arm}	1.35×10^{-1} m
L_{beam}	8.25×10^{-1} m	I_{pxo}	2.55×10^{-5} kgm^2
I_{11}	4.46×10^{-9} m^4	I_{pyo}	1.25×10^{-5} kgm^2
I_{22}	4.62×10^{-8} m^4	I_{pzo}	1.25×10^{-5} kgm^2
g	9.81 ms^{-2}	N_b	3
E	70.00 GPa	m_a	1.40×10^{-2} kg





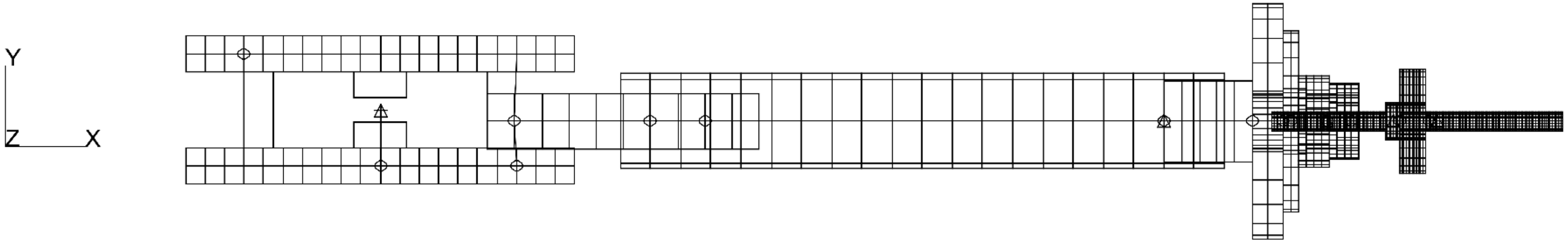
Numerical Modelling *(MSC NASTRAN/PATRAN)*

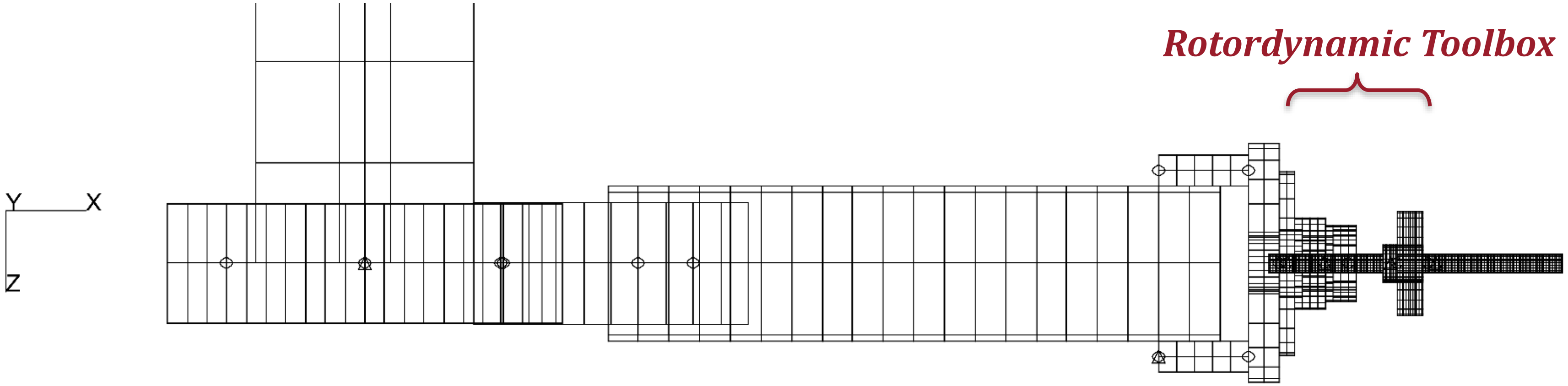
- ✓ 1D beam elements
- ✓ CONM2 (Lumped Mass)
- ✓ CBUSH
- ✓ RBE2 (MPC)
- ✓ *Rotordynamic Toolbox*

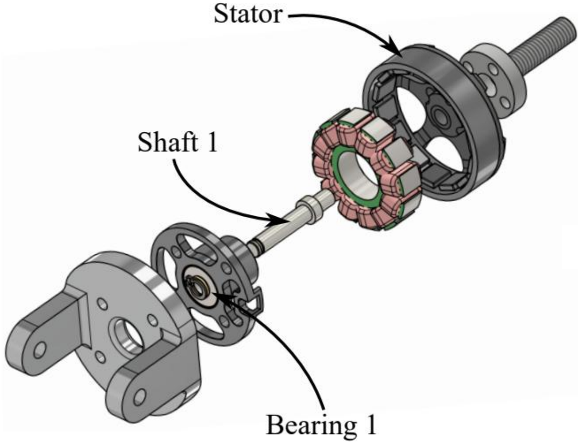


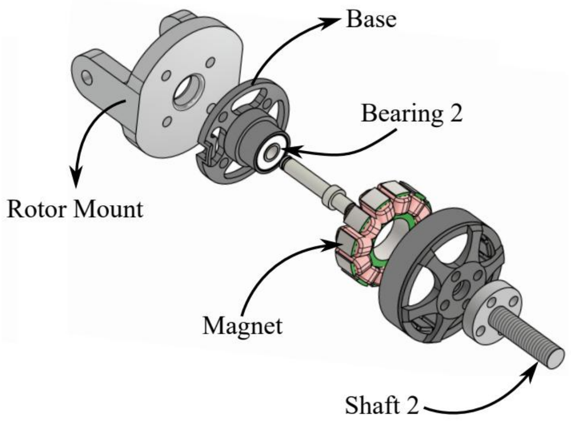
(a) 1D Beam Elements Model (b) 3D Visualisation

Numerical Modelling (3D Visualisation)

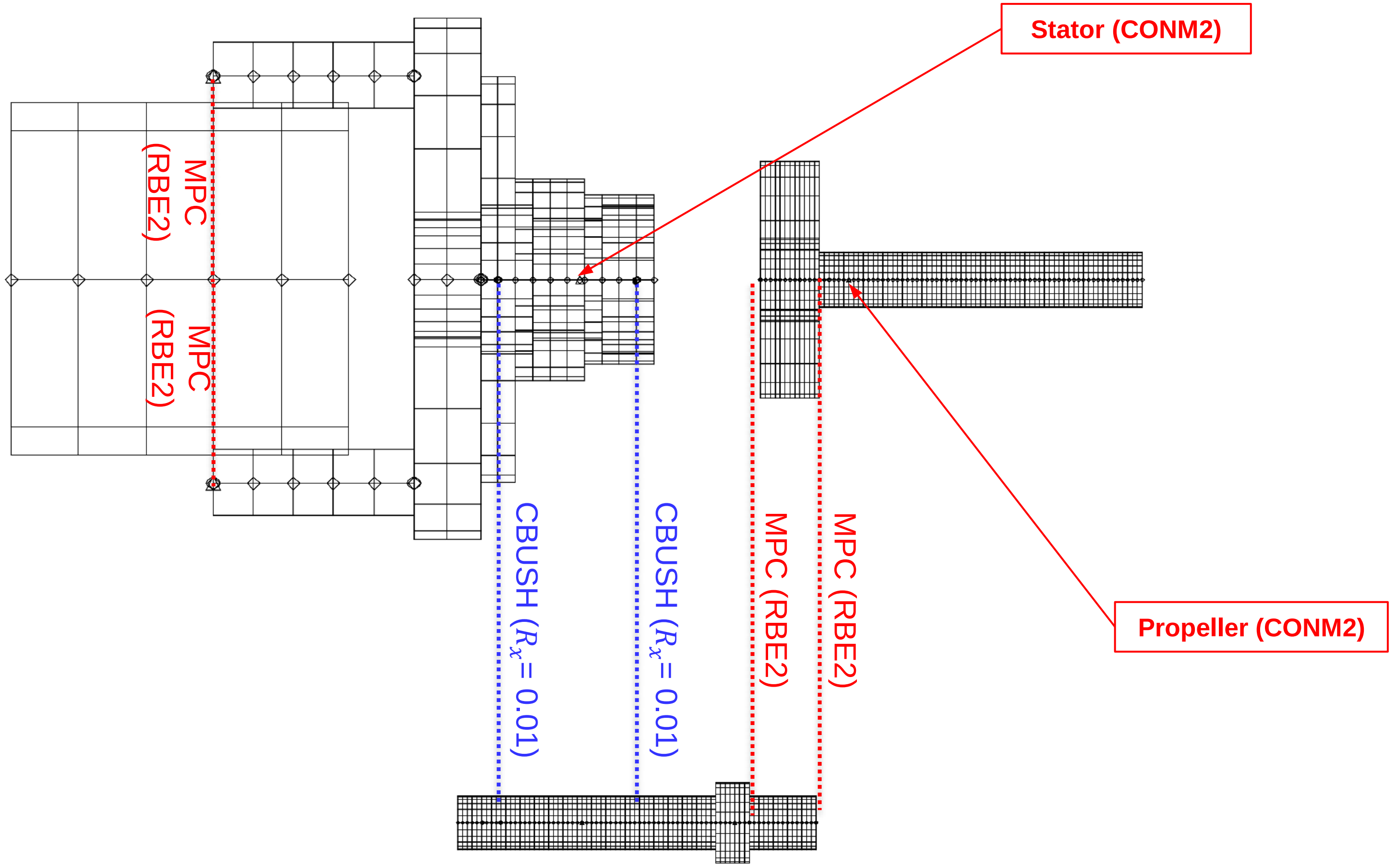






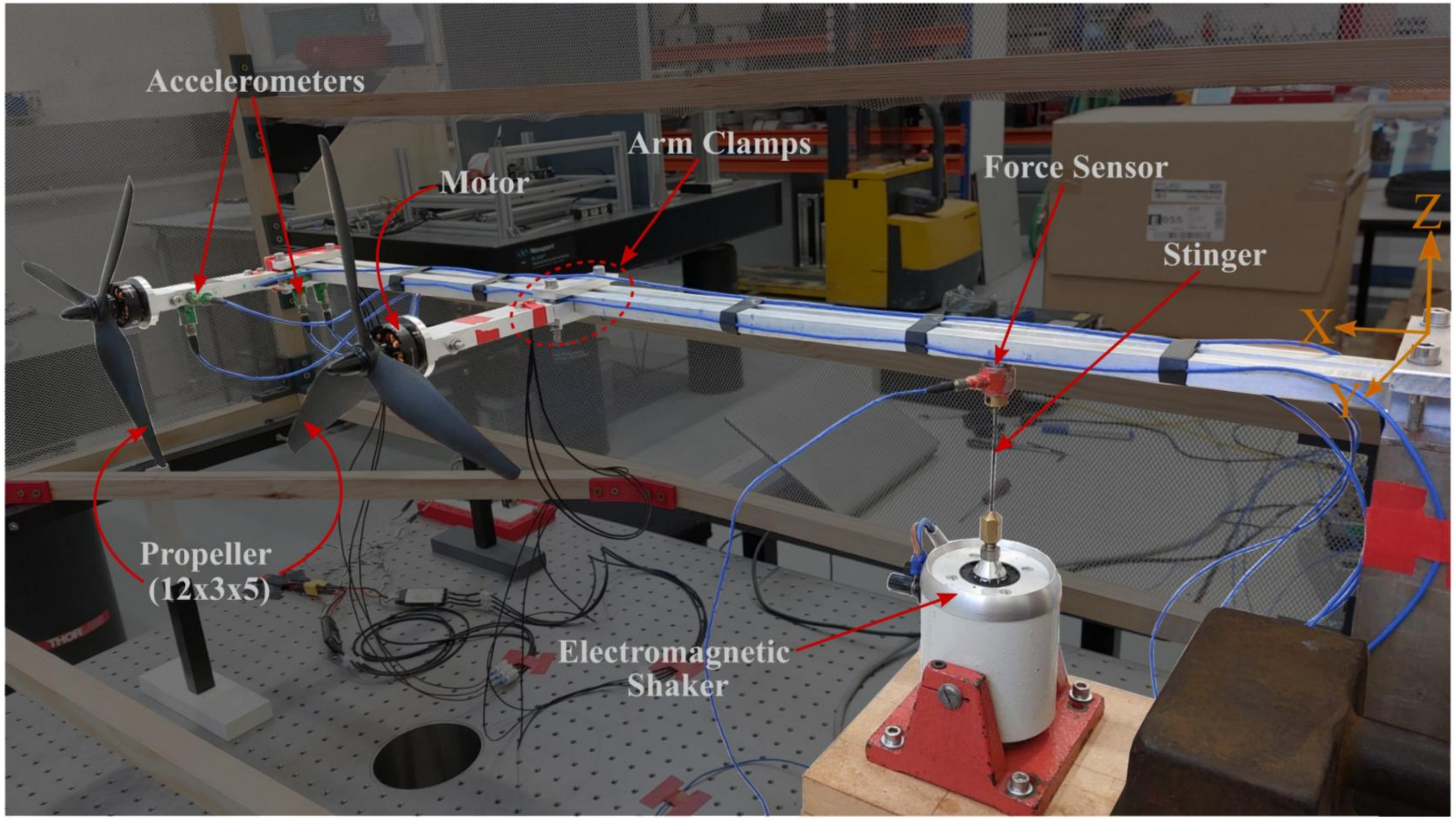


NASTRAN Rotordynamics Model

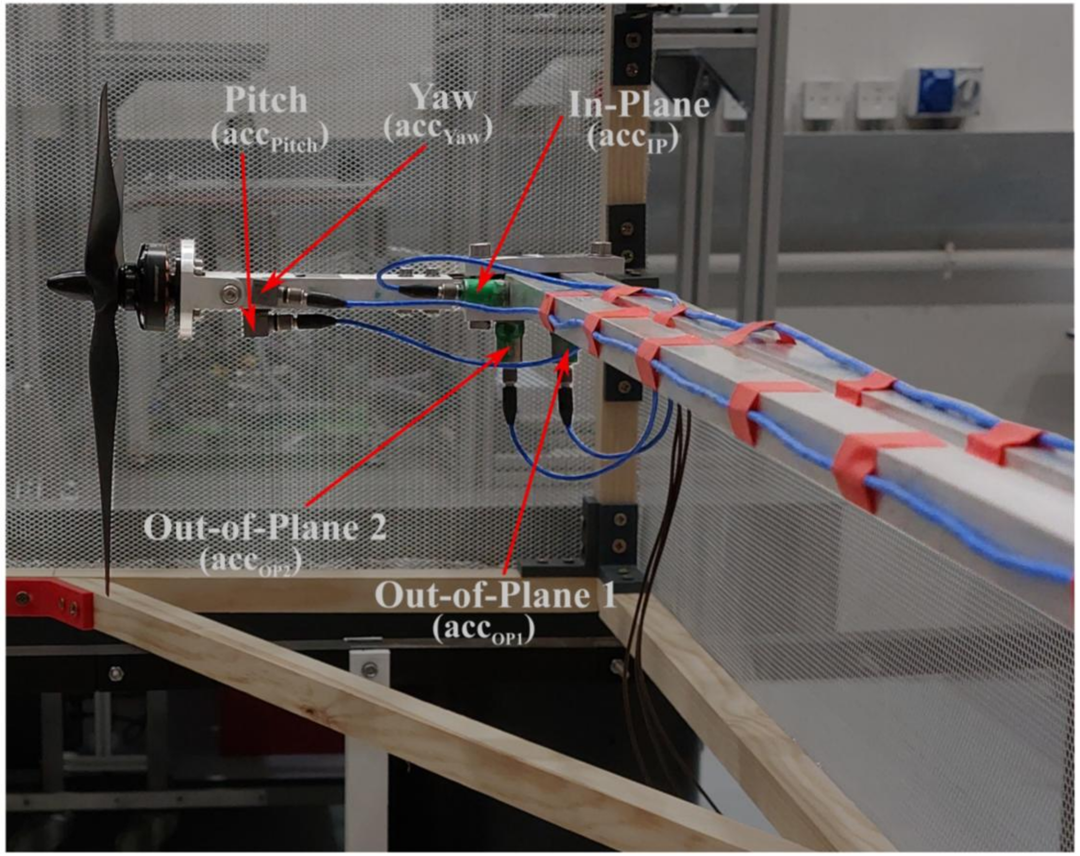


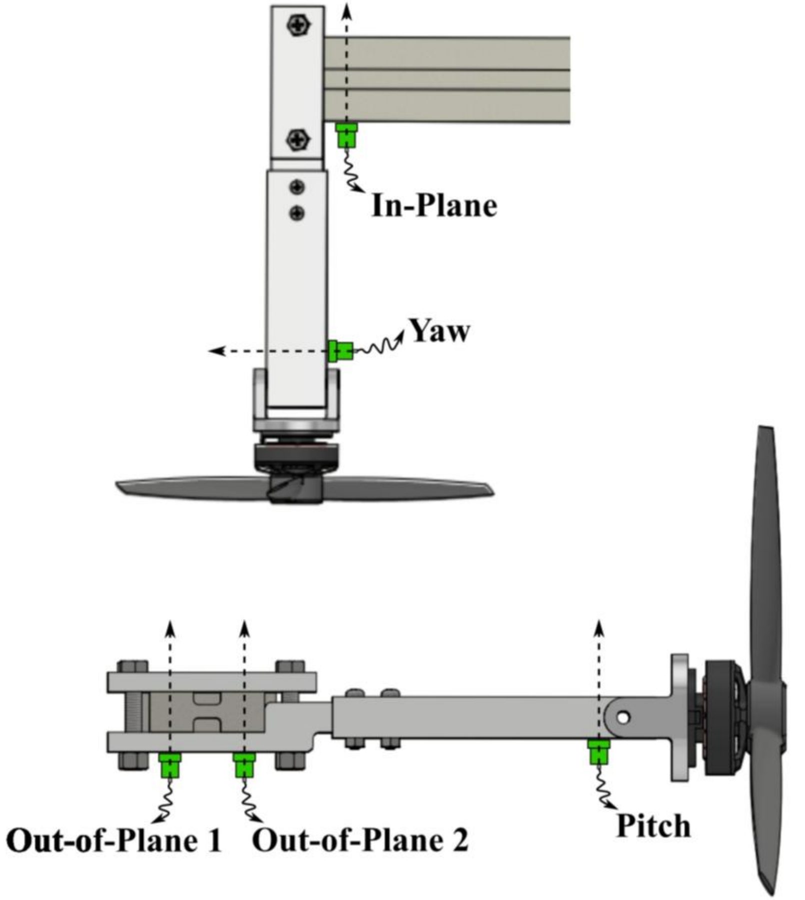
Experimental Setup – Shaker Test

- **Automated Shaker:**
  - ✓ Synchronized motor control
  - ✓ Open loop control (PWM-RPM).
- First rotor assembly at beam tip
- Second rotor 60%, 50% & 40% beam length

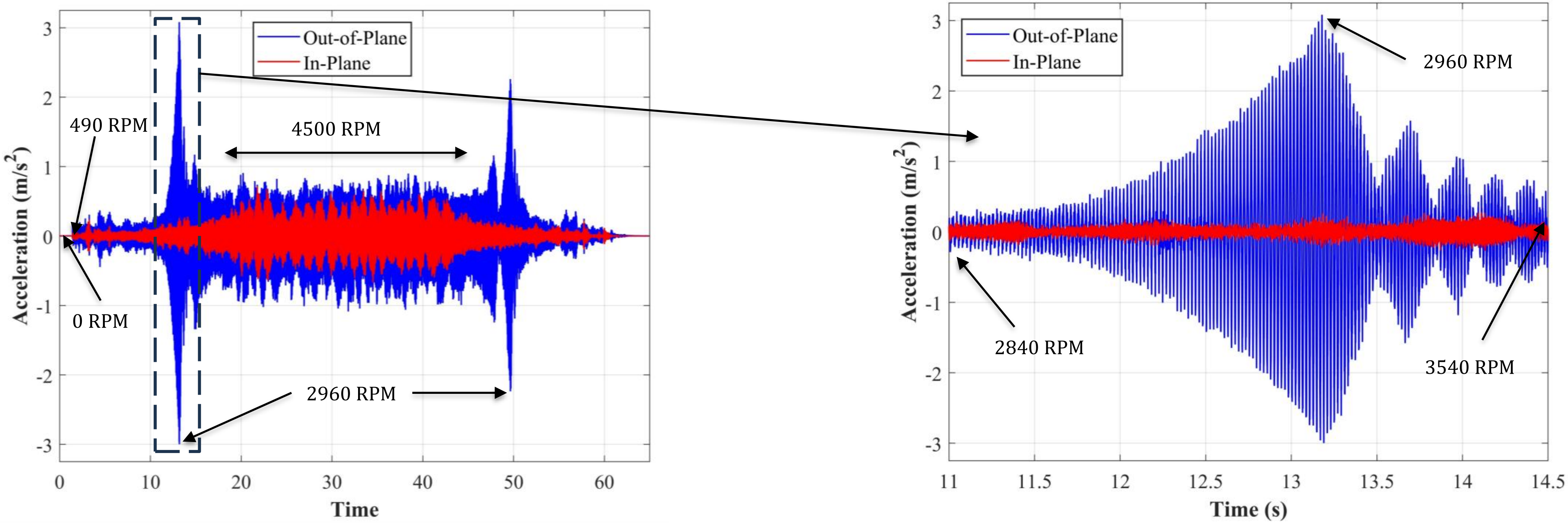


Experimental Setup – Accelerometer Arrangement



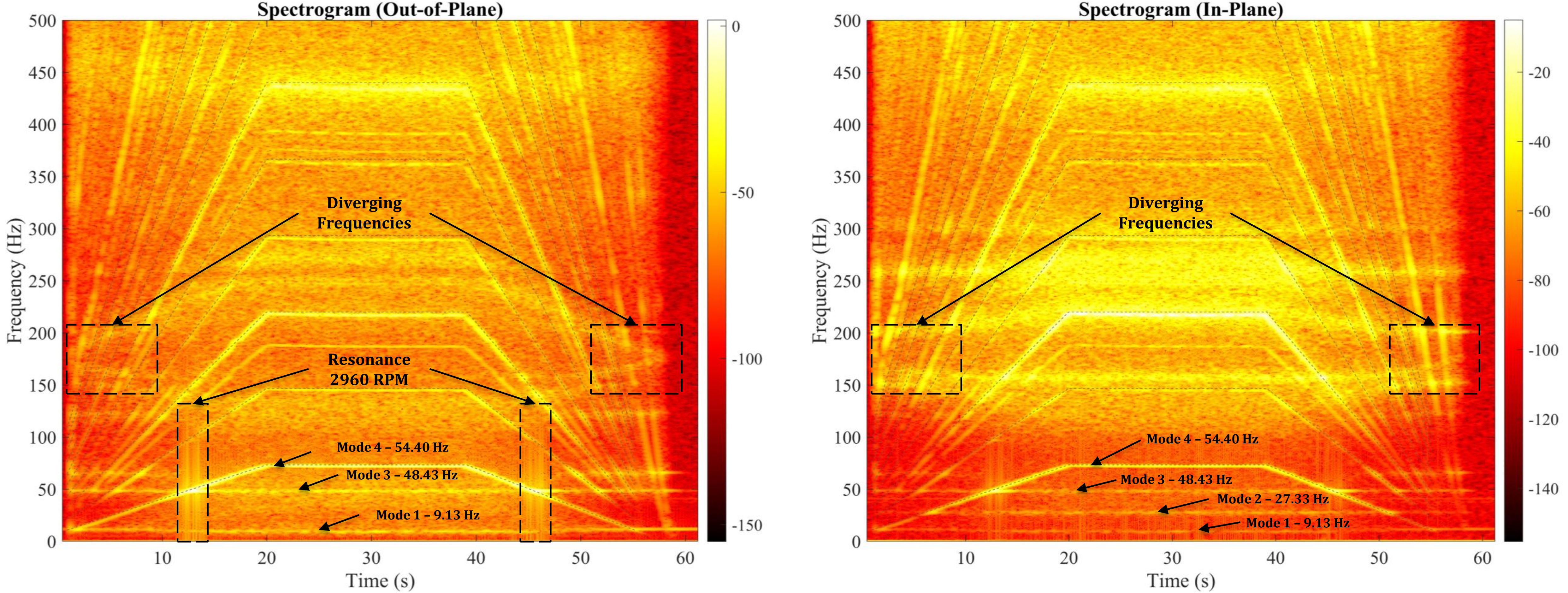


Results – Transient Analysis

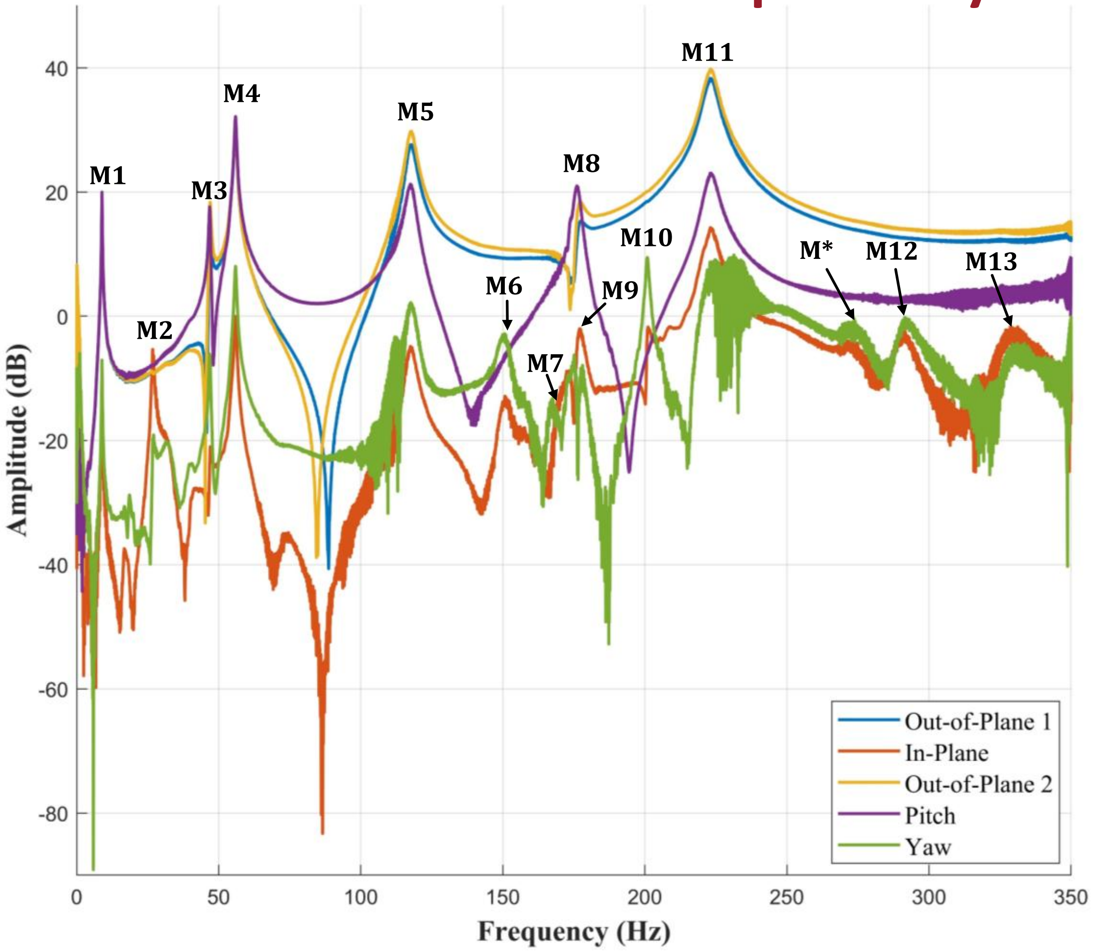


1. **Quiescent State (0-1s):** 0 RPM, quiescent state.
2. **Acceleration (1-16s):** 465 to 4550 RPM → Out-of-plane acceleration.
3. **Resonance Region (12-13.5 s):** Peak at 3120 RPM (52 Hz), OP-2 mode.
4. **Steady-State (16-46s):** 4550 RPM constant, acceleration stabilizes.
5. **Deceleration (46-61s):** RPM decreases to 0.

Results – Spectral Analysis



Results – Frequency Response Analysis (0 RPM)



Inner rotor located at 60% beam length

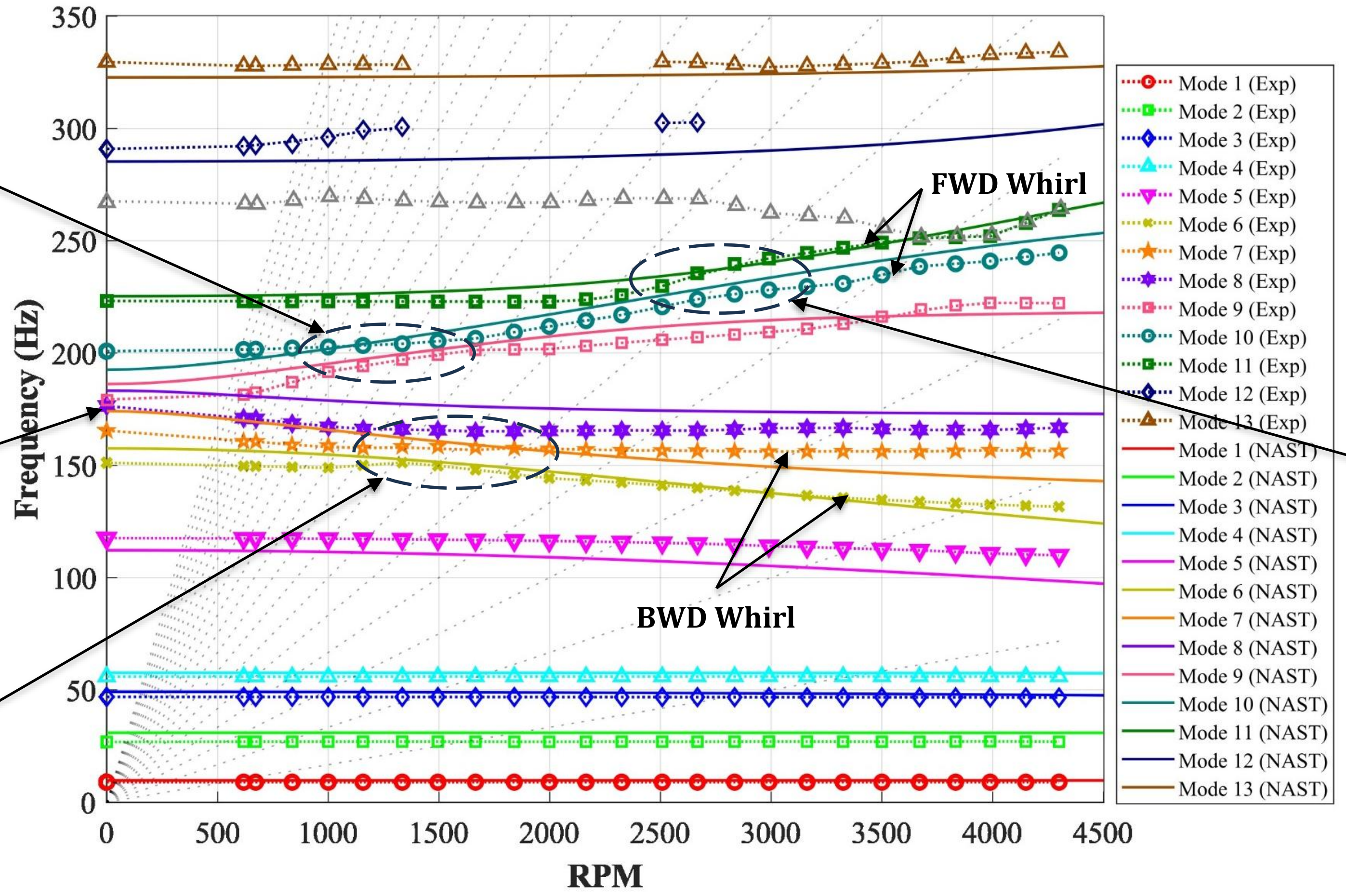
Mode	Type	Frequency [Hz]		Error (%)
		Experiment	NASTRAN	
M1	Out-of-Plane 1	9.13	9.67	-5.93%
M2	In-Plane 2	28.81	30.30	-5.16%
M3	Torsion 1	46.87	49.13	-4.81%
M4	Out-of-Plane 2	55.9	57.64	-3.11%
M5	Out-of-Plane 3	117.59	112.18	4.60%
M6	In-Plane 2	151.15	157.51	-4.21%
M7	Yaw 1	165.45	174.11	-5.23%
M8	Torsion 2	175.5	183.24	-4.41%
M9	Pitch 1	176.39	186.19	-5.56%
M10	Yaw 2	200.75	192.56	4.08%
M11	Out-of-Plane 3	223.17	225.29	-0.95%
M*	-	274.46	-	-
M12	Yaw 3	290.85	282.24	2.96%
M13	In-Plane 3	329.55	321.23	2.53%

Results – *Campbell Diagram (Rotor 2 at 60%)*

Mode Veering 1
- ✓ 650 – 2300 RPM
- ✓ Mode 9 - Pitch 1
- ✓ Mode 10 - Yaw 2

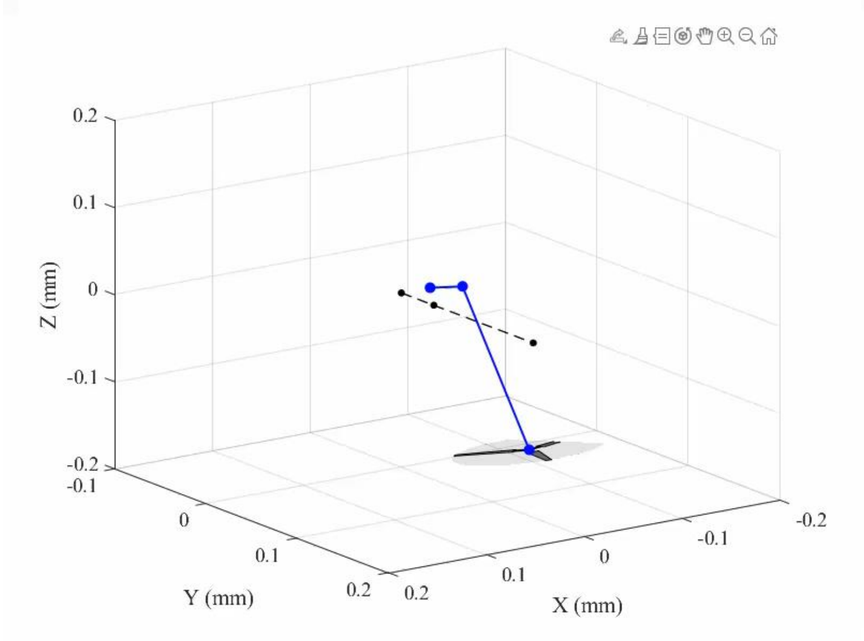
Mode splitting effect from both rotors' co-incident

Mode Veering 2
- ✓ 1100 – 2300 RPM
- ✓ Mode 6 - In-Plane 2
- ✓ Mode 7 - Yaw 1

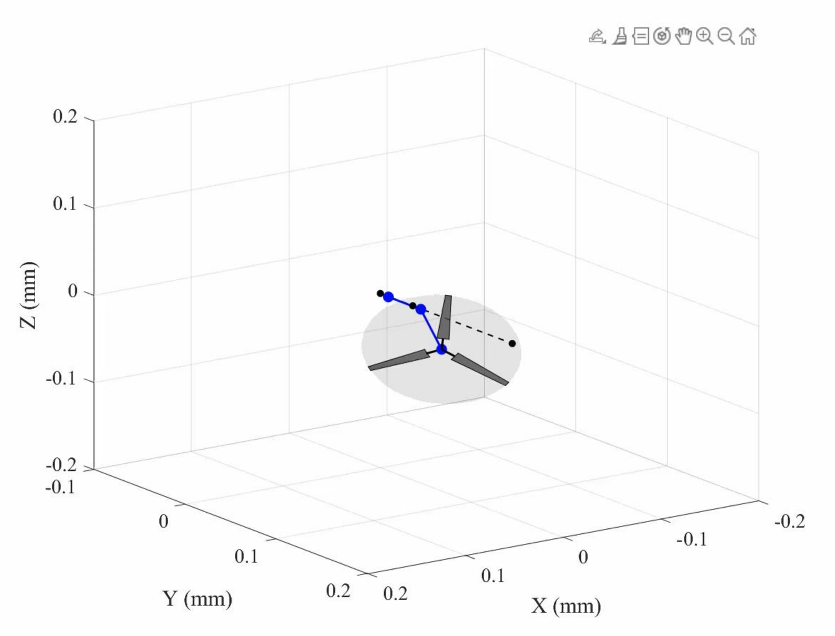


Mode Veering 3
- ✓ 2300 – 4500 RPM
- ✓ Mode 10 - Yaw 2
- ✓ Mode 11 - Pitch 3

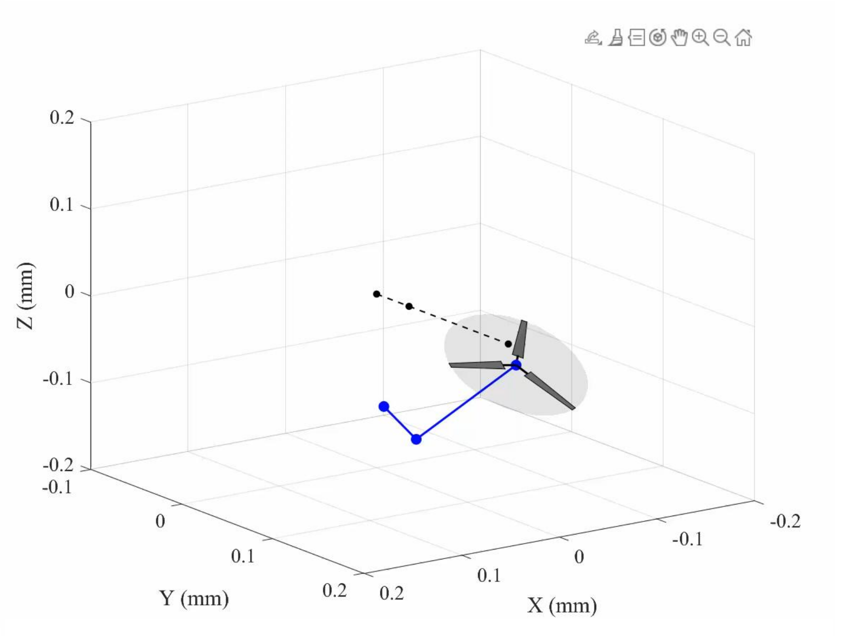
Results – Mode Shapes – Veering (550 RPM)



Mode 9
550 RPM

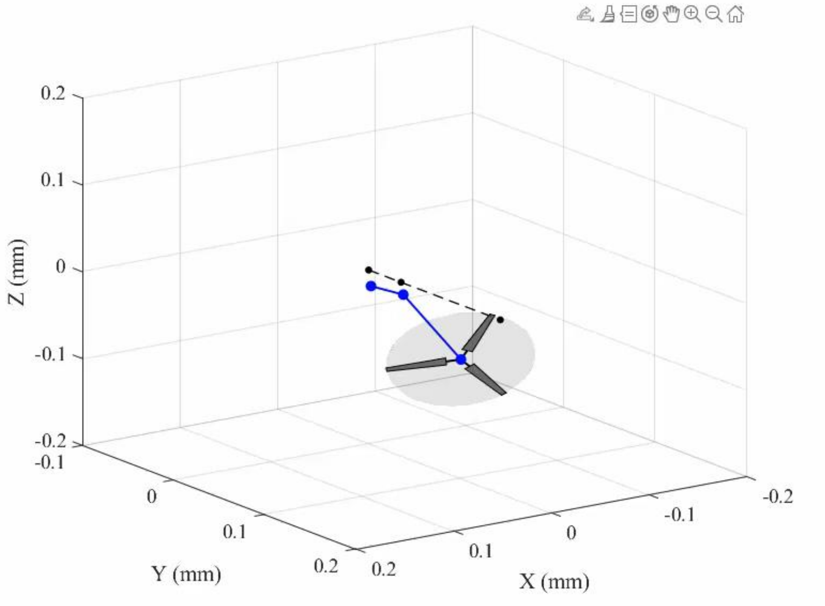


Mode 10
550 RPM

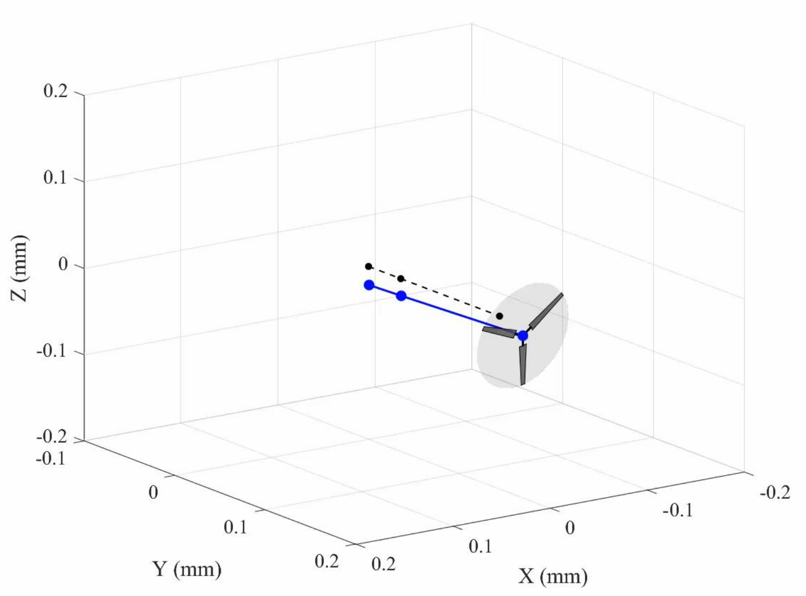


Mode 11
550 RPM

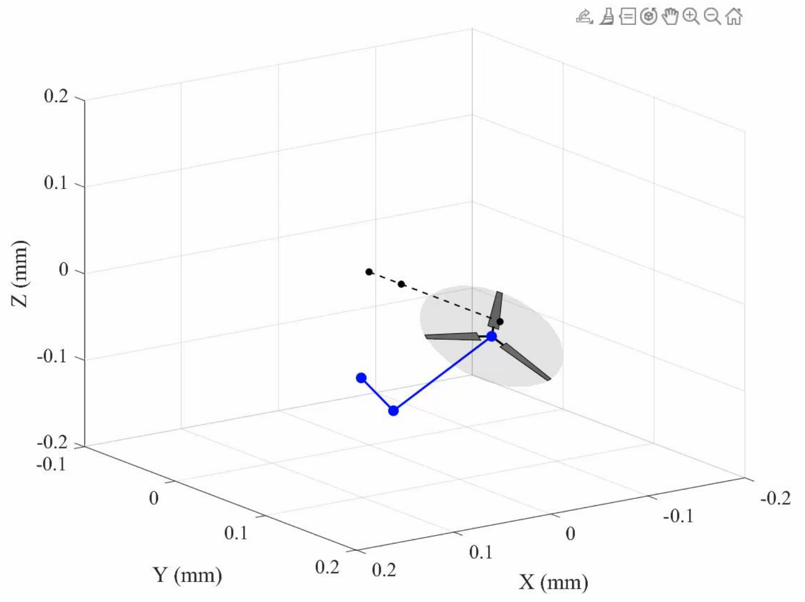
Results – Mode Shapes – Veering (1600 RPM)



Mode 9
1600 RPM

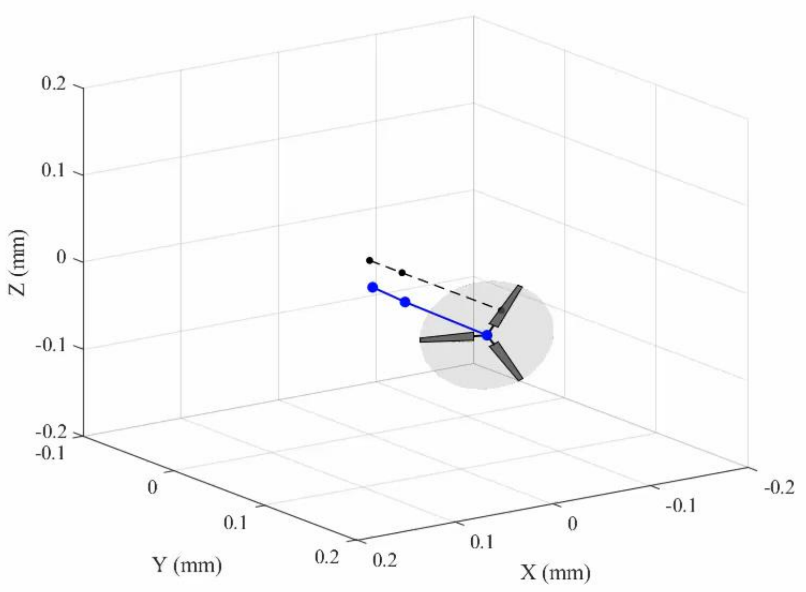


Mode 10
1600 RPM

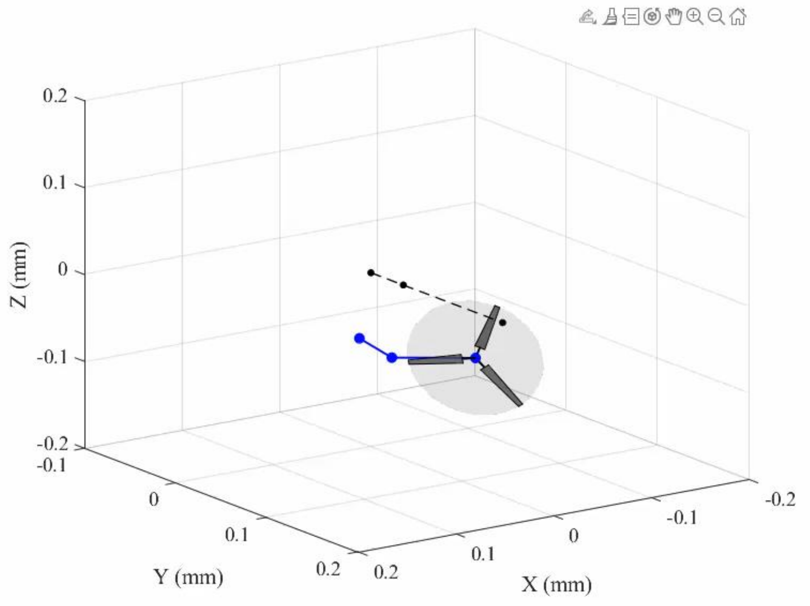


Mode 11
1600 RPM

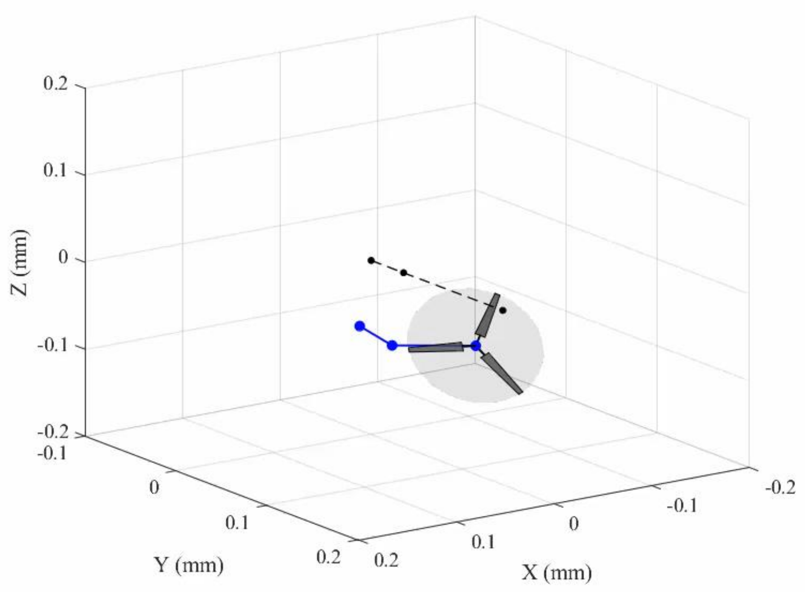
Results – Mode Shapes – Veering (2300 RPM)



Mode 9
2300 RPM

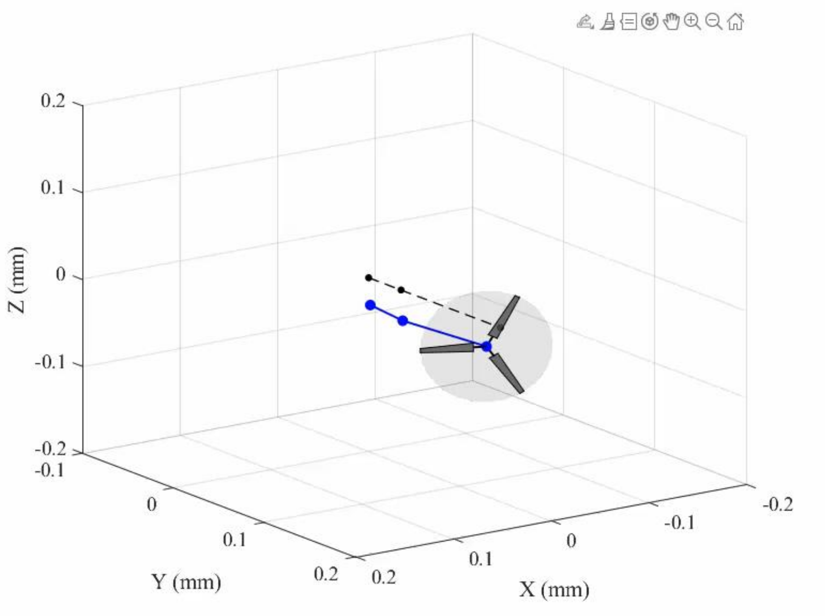


Mode 10
2300 RPM

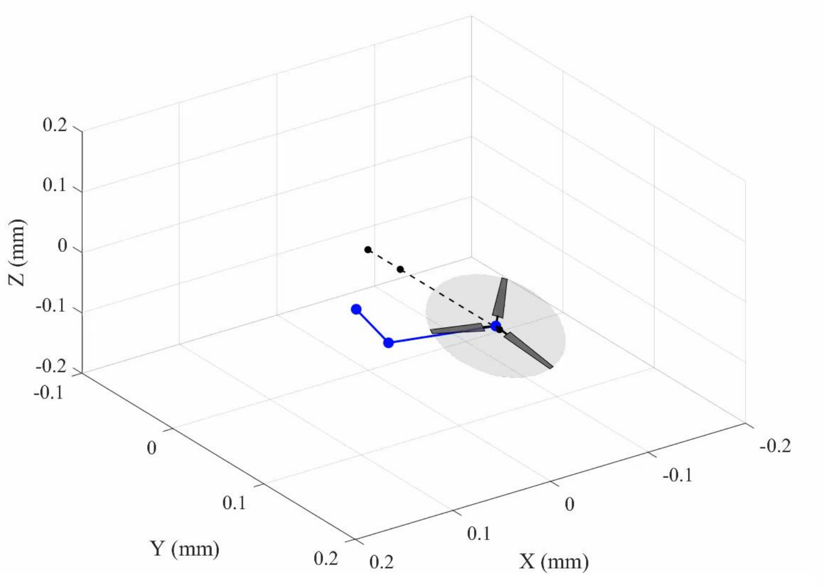


Mode 11
2300 RPM

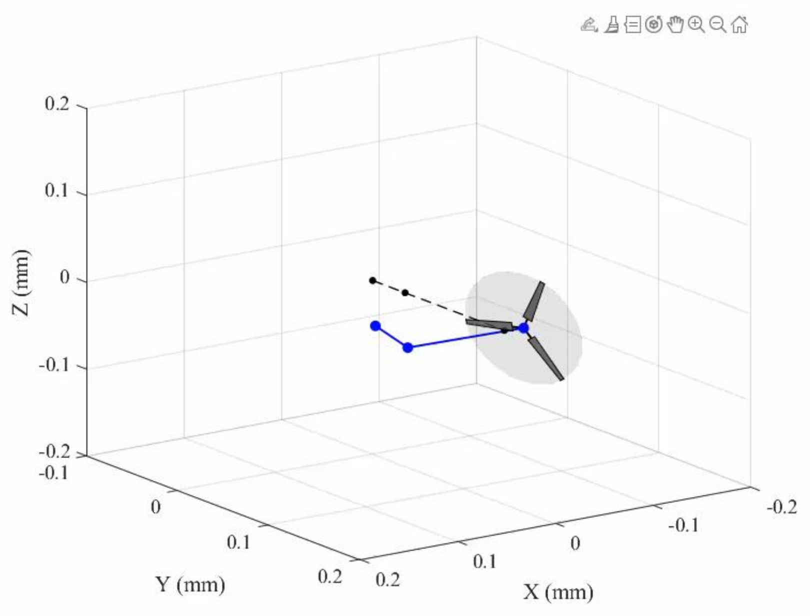
Results – Mode Shapes – Veering (2600 RPM)



Mode 9
2600 RPM



Mode 10
2600 RPM



Mode 11
2600 RPM

Conclusions

- Demonstrated a **controlled experimental framework** for investigating rotor–rotor dynamic interactions in multirotor eVTOL structures using a dynamically scaled rig.
- Identified and characterised **distinct mode veering interactions** across multiple rotor spacing cases (40%, 50%, 60% span), confirmed via both experiment and NASTRAN-based complex eigenvalue analysis.
- Captured **clear forward and backward whirl separation** in experimental Campbell diagrams, validating whirl predictions from reduced-order beam models.
- Showed that **rotor spacing significantly alters coupling patterns**, with modal coalescence zones shifting across RPM range.

- Future work

Acknowledgements

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- Project Supervisors:
  - Dr. Djamel Rezgui – *Associate Professor, Department of Aerospace Engineering, University of Bristol.*
  - Dr. Branislav Titurus – *Associate Professor, Department of Aerospace Engineering, University of Bristol.*

Thank You

Questions?