Characterisation Of Tiltrotor Blade Aerodynamic and Aeroelastic Behaviour In Propeller Mode At Stalled Conditions

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Outline of Presentation

- **Introduction**
  - Research Motivation
- **Experimental Setup**
  - United Kingdom National Rotor Rig (University of Glasgow)
  - Test Matrix
- **Results**
  - Blade Strain
  - Performance Measurements
  - Blade Tip Deflections
- **Conclusions**

Research Motivation

eVTOL

Tiltrotors

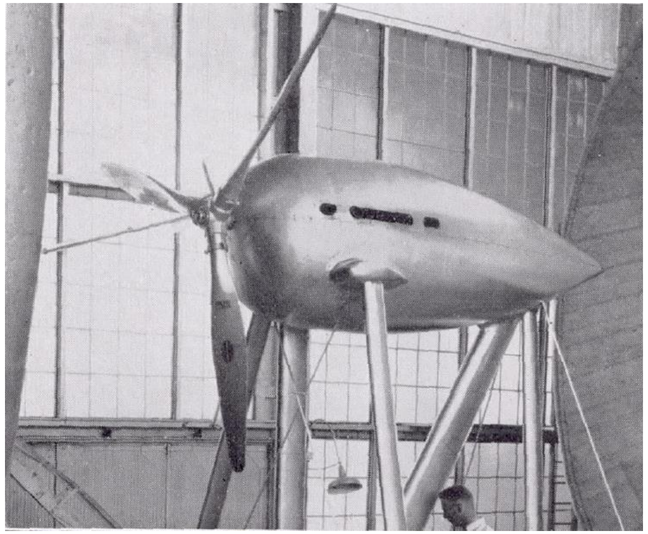
- Development of unconventional rotorcraft configurations
  - Bell V-280 tiltrotor to replace UH-60 for US Army
  - Rapid growth of civilan eVTOL market

- Tiltrotor blades are required to operate as propellers and rotors
  - Underexplored regions of the flight envelope
  - Newly developed thin and twisted shapes

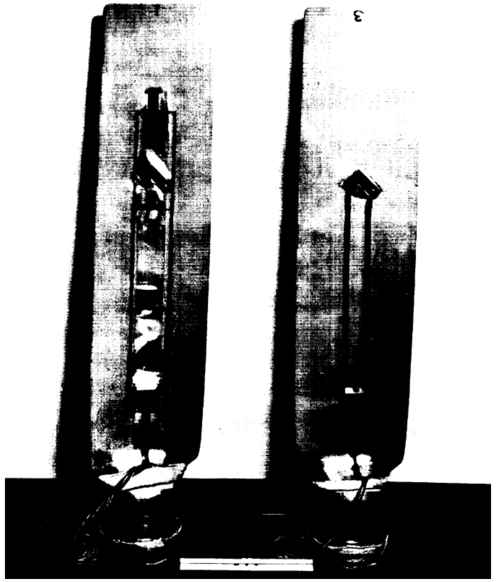
- Further understand expected blade performance:
  - Aerodynamic boundaries (e.g blade stall)
  - Aeroelastic boundaries (e.g stall flutter)

Research Motivation

- Formation of modern aerodynamic and aeroelastic databases
    - Lack of experimental data for modern CFD validation
    - Clearly defined blade geometries and blade structural properties
    - Aid certification of new aircraft concepts
    - Utilise state-of-the-art experimental methods



Wooden blades with undefined structural properties (Hartman et al.)



Unoptmised blades instrumented with externally mounted strain gauges (Rogallo et al.)

Scope of Investigation

Undertake a multi-measurement experimental approach to characterise the aerodynamic performance and blade structural response of the MENtOR tiltrotor blades in propeller mode

- Carried out at University of Glasgow 9ft x 7ft DeHavilland wind tunnel
- Variation of rotational frequency (Ω), Advance ratio (J) and blade pitch at 0.75R ($\beta_{0.75R}$)
- Unsteady blade strain measurements obtained from instrumented blade set
- Thrust and torque data logged via Rotating Shaft Balance (RSB)
- Blade tip deflections measurements obtained via stereoscopic Digital Image Correlation (DIC)

UK National Rotor Rig

- Recently modified to fixed pitch propeller rig
- 1.25m diameter up to tip Mach-scaled conditions ($M_{tip} \approx 0.6$ at 3000 RPM)
- Large available power excess to test in deeply stalled conditions
- Telemetry system to transmit blade strain gauge and RSB data from rotating to stationary frame

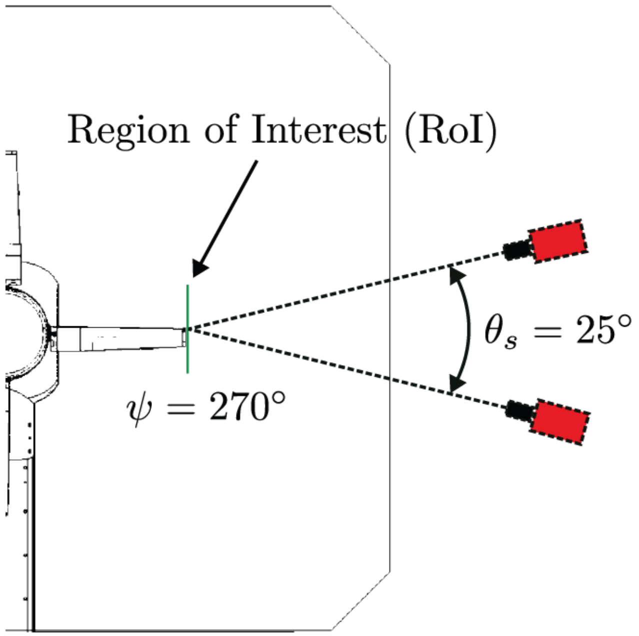
Maximum Operational Limit	Quantity	Units
Thrust	3400	N
In-Plane Forces	550	N
Torque	350	Nm
In-Plane Moments	250	Nm
Available Power	125	kW
Rotational Frequency	3000	RPM
Pitch Angle Range	[-5,40]	°

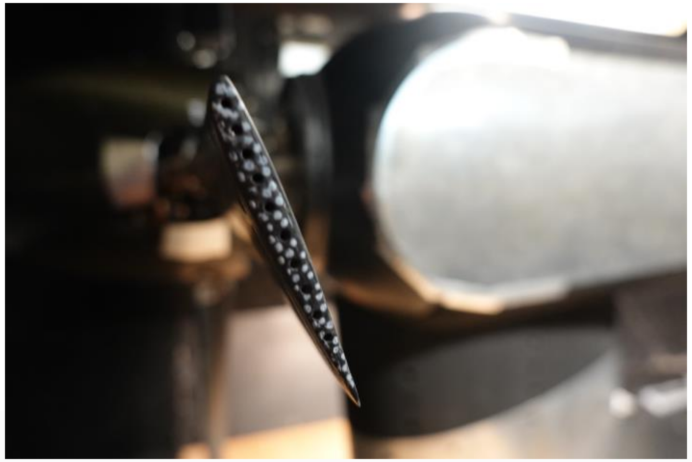
Digital Image Correlation

- Stereoscopic imaging to assess blade tip deflections
  - Stereo angle of $\theta_S = 25^{\circ}$
  - Phase locked at $\varphi = 270^{\circ}$ using Hall-effect sensor

- Randomised speckle dot pattern applied to blade tip
  - Bending displacement and torsional twist obtained via image correlation

- Optical parameters
  - 5 Mpixel GigE-Prosilica CMOS cameras
  - 200 images per test condition
  - Magnification factor = 7.35 px/mm





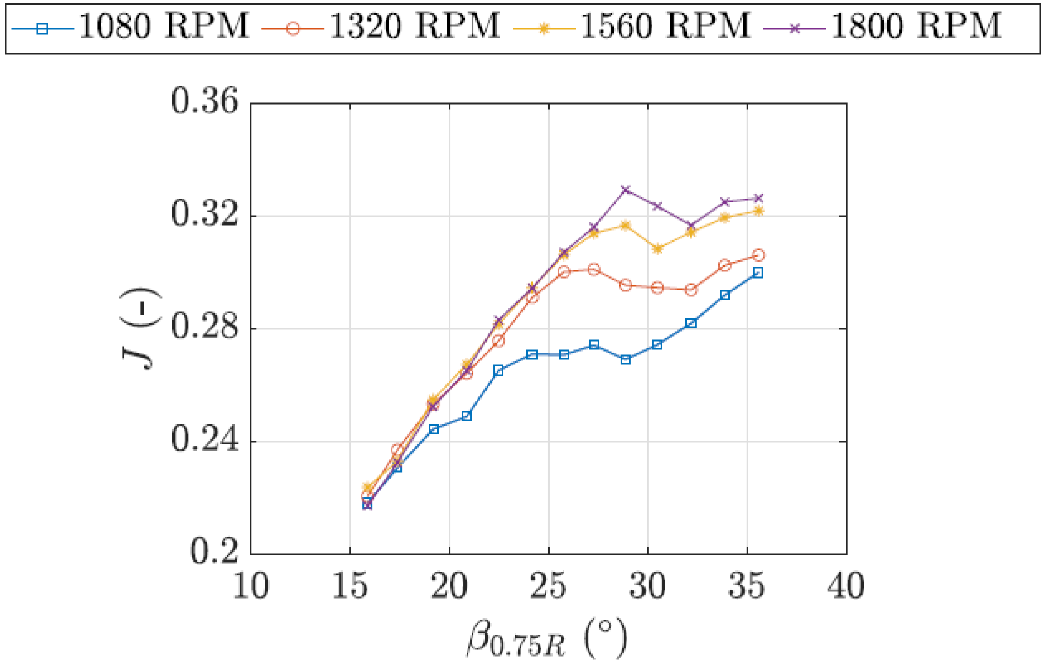
Test Matrix

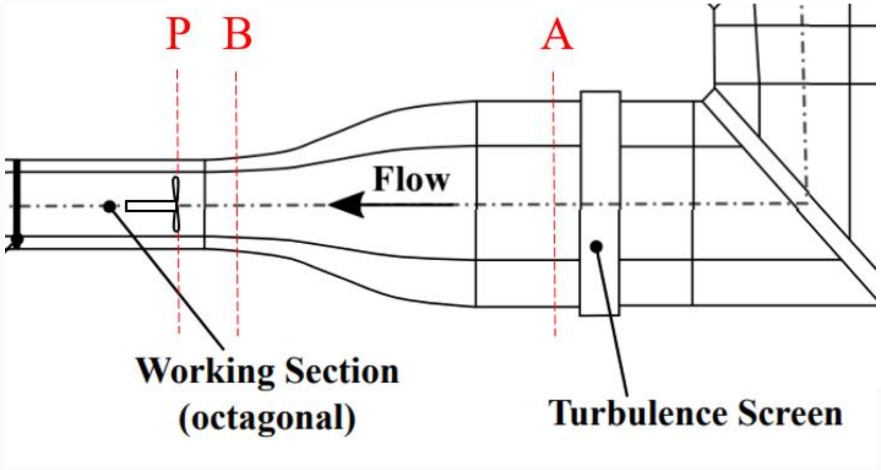
- Three parameters:
  - Rotational frequency, $\Omega = 1080$ to 1800 RPM, $\Delta\Omega = 120$ RPM
  - Advance ratio, $J = \frac{U_\infty}{nD}$
  - Blade pitch, $\beta_{0.75} = 16^\circ$ to 35.7°

$\beta_{0.75R}$	No WT	J=0.5	J=0.7	J=0.9	J=1.1	J=1.3
16^o	X	X				
19.1^o	X	X	X			
22.3^o	X	X	X	X		
25.5^o	X	X	X	X	X	
28.7^o	X	X	X	X	X	X
32^o	X	X	X	X	X	X
35.7^o	X	X	X	X	X	X

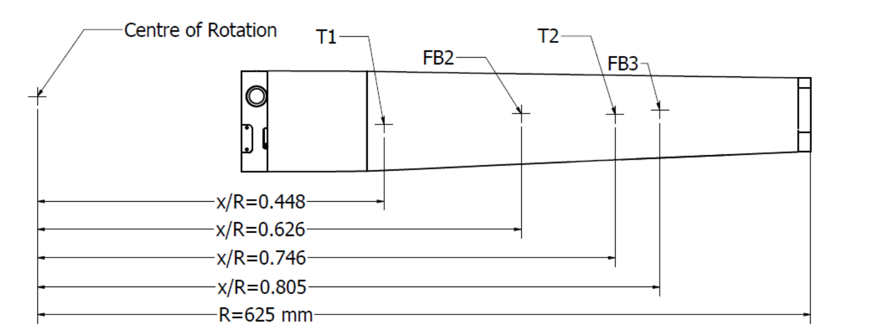
Results - Wind Tunnel Velocity Reference

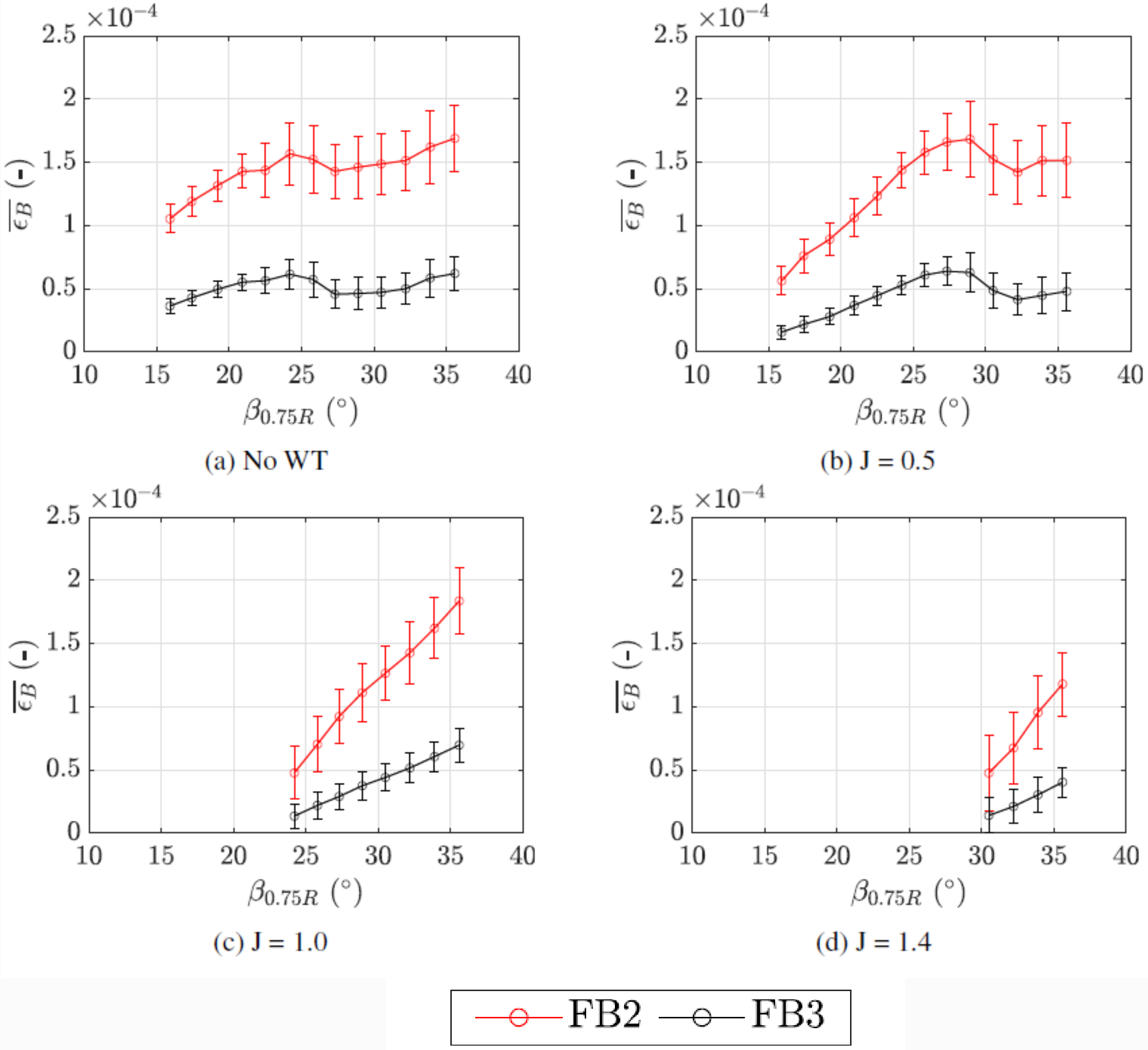
- Closed return wind tunnel
- Max U_∞ = 70 m/s, empty test section, $J = \frac{U_\infty}{nD}$
- Propeller induces velocity around the loop
- Calibration of contraction ring to set wind speed
- UKNRR rig acts as secondary fan





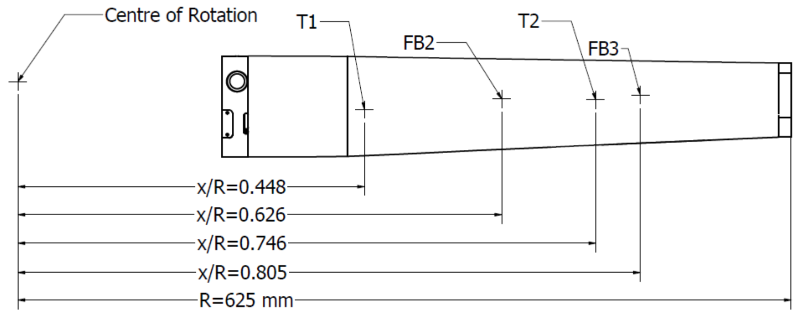
Results – Strain Gauge

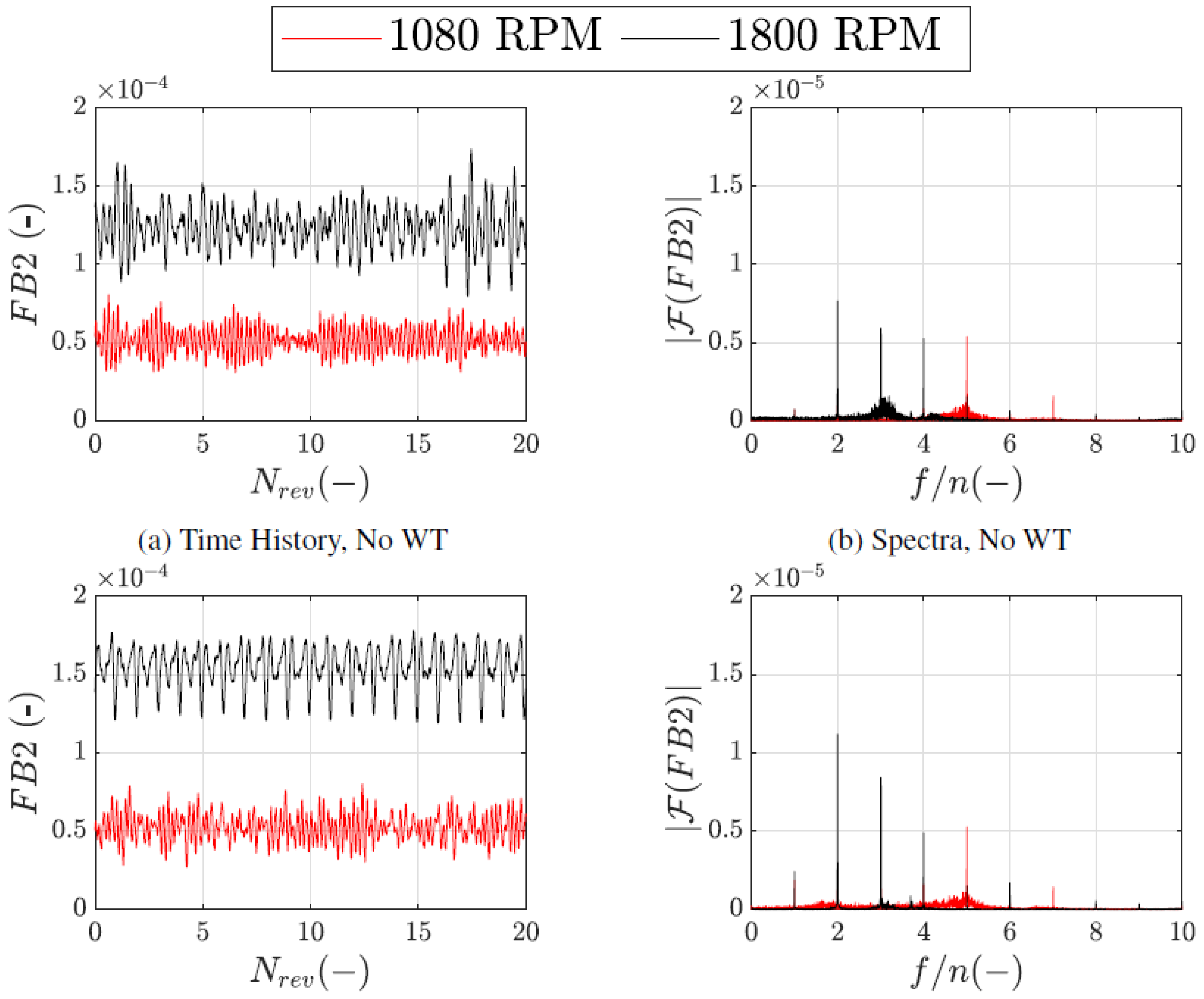




- $\Omega = 1080$ RPM
- **Compensated strain** $\overline{\epsilon_B} = \epsilon_B \frac{\bar{\rho}}{\rho}\left(\frac{\bar{\Omega}}{\Omega}\right)^2$
  - $\bar{\rho} = 1.225\ \frac{kg}{m^3}$
  - $\bar{\Omega} = 1800\ RPM$
  - Equivalent dynamic pressure
- Stall indicators
  - Deviation from linear behaviour
  - Growth in standard deviation post stall

Results – Strain Gauge





(a) Time History, No WT

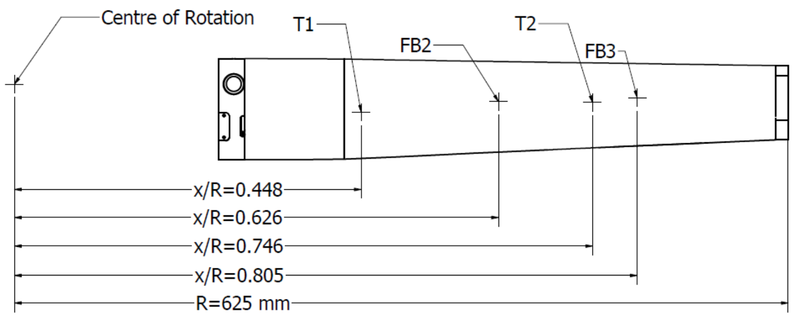
(b) Spectra, No WT

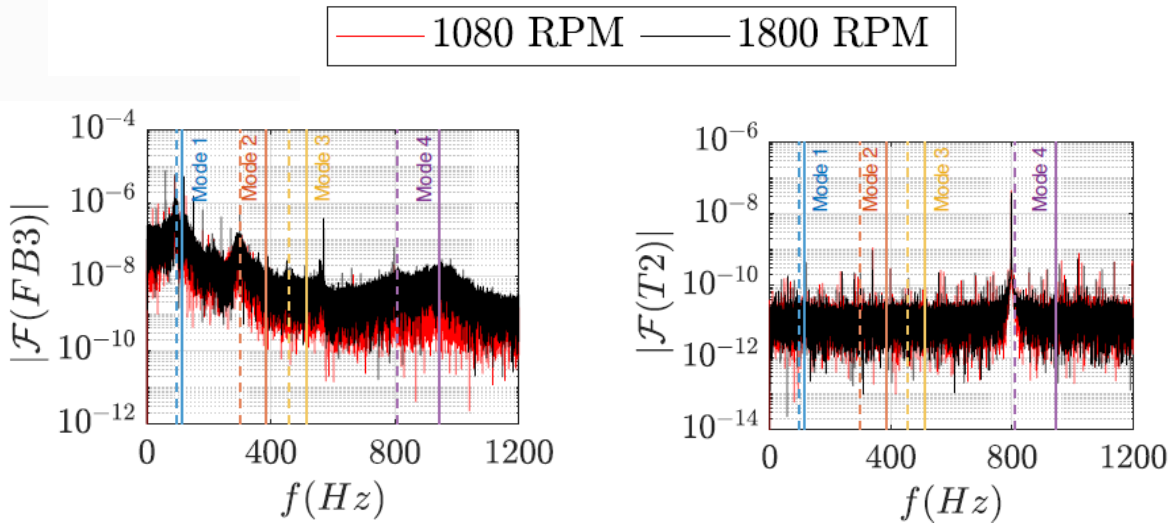
(c) Time History, J = 0.5

(d) Spectra, J = 0.5

- $\beta_{0.75} = 30.5^{\circ}$
- No WT case shows presence of stall
  - Irregular pattern and amplitude
  - Distribution of signal energy across broadband of frequencies
- J = 0.5 shows stall at 1080 RPM
  - 1800RPM has repeatable pattern of constant amplitude with dominant 1/rev spike
  - FFT of 1800 RPM shows only harmonics

Results – Blade Modes



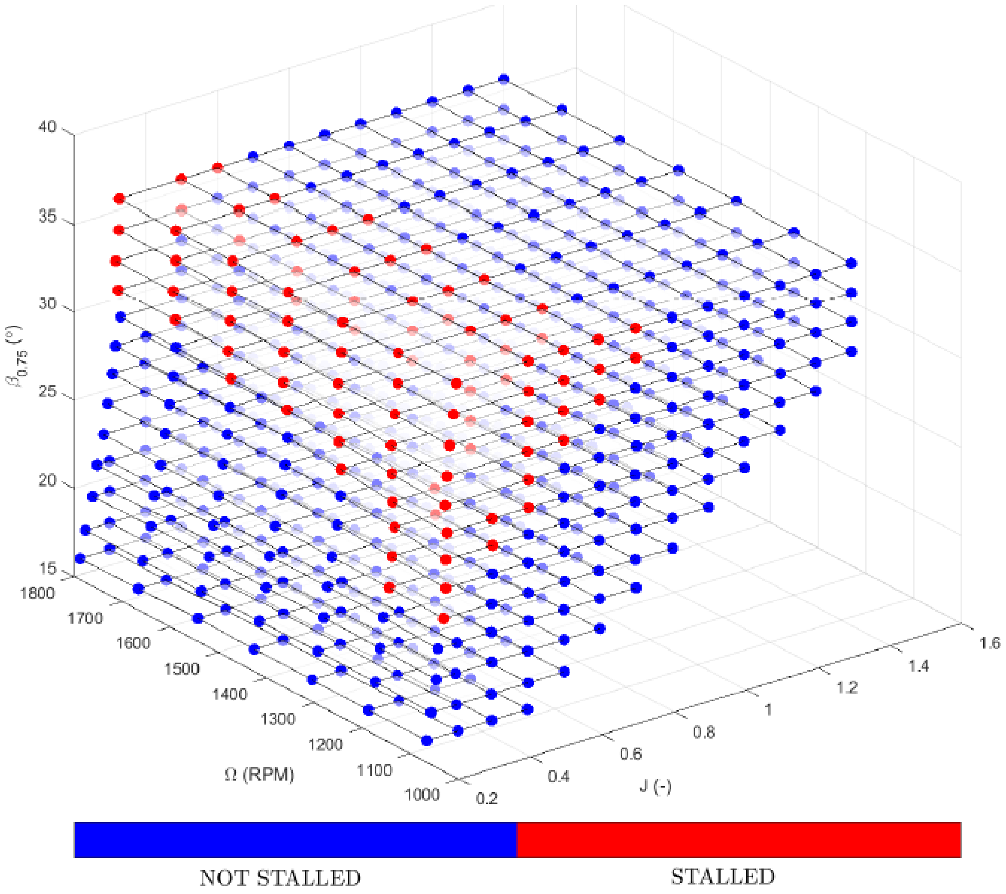


Mode Shape	Mode Number	Range of f_m (Hz)
1st Flap Bending	1	90-100
2nd Flap Bending	2	295-305
3rd Flap Bending	3	452-462
1st Torsion - Flap Bending	4	804-814

- SG data plotted using logarithmic scale
- Solid lines (Numerical) and dashed (Experimental)
- Blade modes identified
  - 1st peak at 90-100 Hz which translates to non-dimensional frequency of 3/rev @ 1800 RPM (30Hz) and 5/rev @ 1080 RPM (18Hz)
  - Stall cell shedding manifest as excitation of 1st flap bending mode
  - Blade torsional excitation needed to a excite a modal response such as stall flutter is large for rigid blades

Results - Stall Boundary Criteria

- **Collapse of induced velocity** around WT loop
- **Departure from linear behaviour** of the flap bending strain vs blade pitch curves
- Marked **increase of the standard deviation** of the flap bending strain, up to twice the pre-stalled conditions
- Presence of **non-harmonic content in the strain spectra**, up to 20 % in amplitude of the corresponding harmonic content
- **Non consistent oscillation amplitude** in the strain time history



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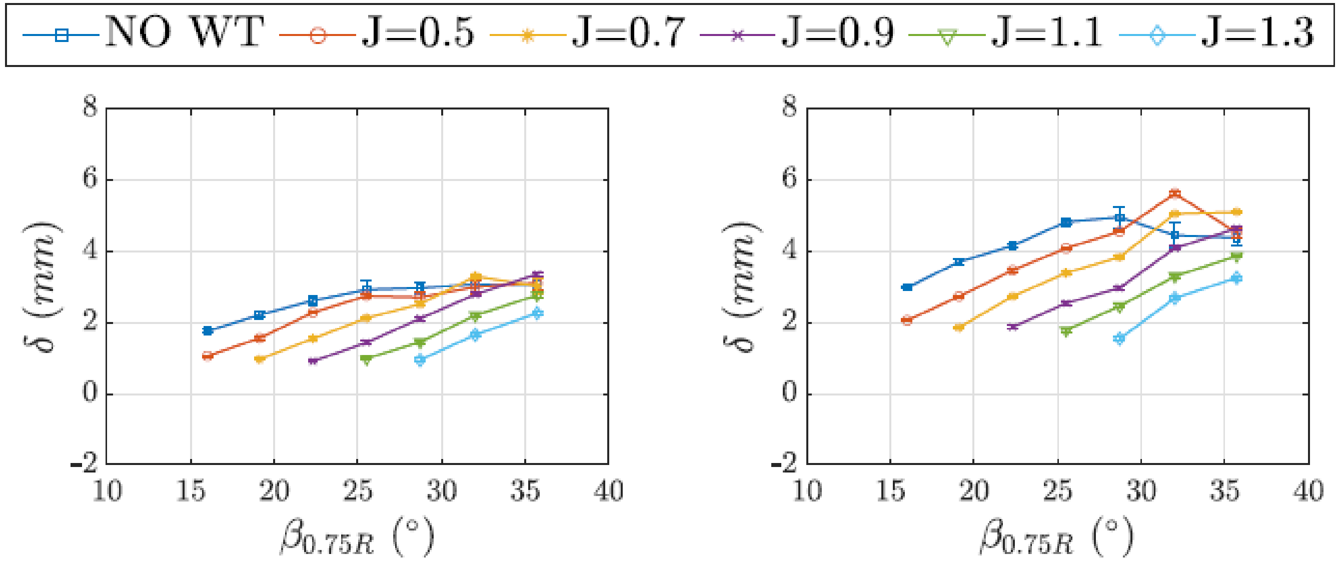
Results – Blade Tip Deflections



Ω = 1080 RPM

Ω = 1320 RPM

- Blade tip bending increased for larger RPM values due to higher loading.
- Flap bending deflections can be used to identify presence of stall
  - Reduction in deflection magnitude
  - Increased measurement unsteadiness represented via error bars.

Conclusions

- Stall onset was identified using a criteria established based upon the behaviour of the following parameters:
  - Induced velocity
  - Bending strain vs blade pitch curves
  - Standard deviation of strain gauge measurements
  - Strain spectra and time histories

- Performance measurements indicated the presence of stall at conditions identified using strain gauge identification criteria

- Flap bending tip deflections can also be utilised to identify stall onset

- Blade eigenmode frequencies can be identified from strain measurements

Thank you for your attention

Any Questions?

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