Measurements of Propeller Aerodynamic and Aeroelastic Behaviour Under Stall Conditions

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Outline of Presentation

- **Research Motivation**
- **Experimental Setup**
  - United Kingdom National Rotor Rig
  - DeHavilland 9ft x 7ft Wind Tunnel
- **Prominent Results**
- **Conclusions**

Research Motivation

- Growth in EVTOL configurations
  - Operation in both rotor and propeller mode
  - Thin and twisted shapes
  - Unexplored regions of the flight envelope

- Further understand blade **aerodynamic and aeroelastic boundaries**
  - Stall and flow separation
  - Negative thrust
  - Reverse flow
  - Flutter and modal excitation

- Can blade structural response provide insight to operational boundaries?

UK National Rotor Rig

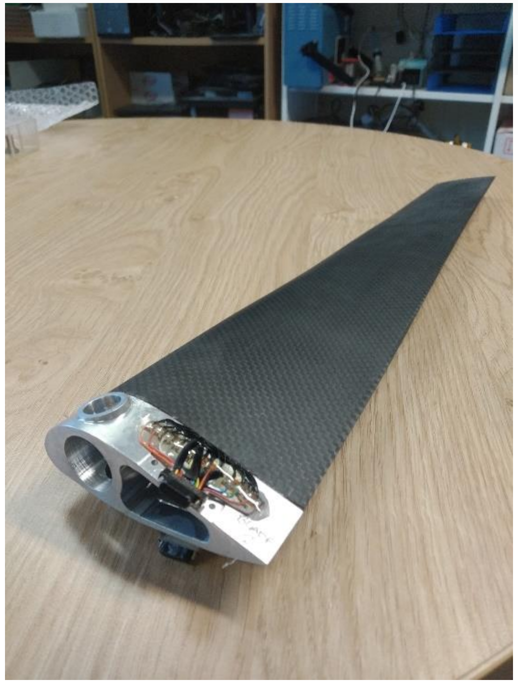
- Integrated into DeHavilland 9ft x 7ft closed return wind tunnel
  - Bespoke steel support structure

- Operational considerations
  - Very high torque and power demand
  - Very large and unsteady loading
  - Mechanical stops to test at fixed blade pitch without cyclic pitch

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]	°

Instrumentation

- 1.25m Diameter Carbon fibre composite tiltrotor blades
  - Internally instrumented with 4 fully bridged axial and shear bridges
  - Full bridges compensate for centrifugal and thermal effects
- Rotating Shaft Balance (RSB)
  - 6 component load-cell situated within the rotor hub
- Datatel Telemetry System
  - 60 measurement channels
  - Power supplied to rotating frame via inductive ring
  - 3mm contact free transmission gap between transmitter to the receiver
  - Sampling rates up to 107kHz



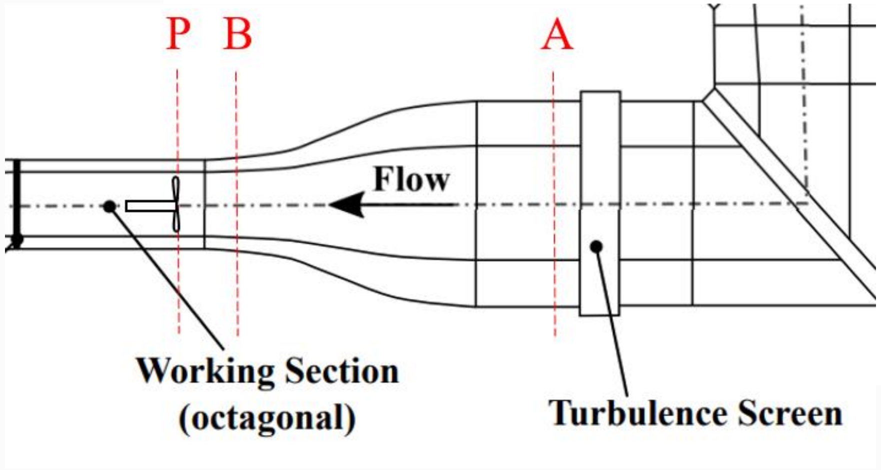
Test Matrix

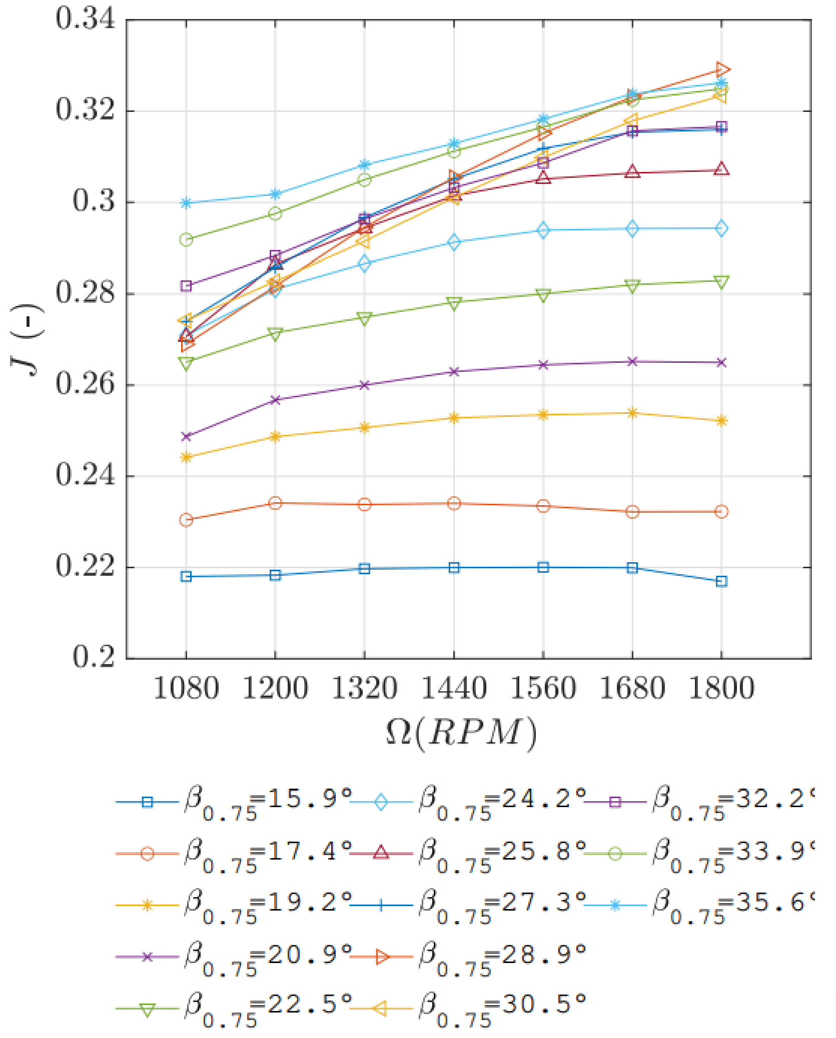
- Three parameters:
  - Rotational frequency, $\Omega = 1080$ to 1800 RPM, $\Delta\Omega = 120$ RPM
  - Advance ratio, $J = \frac{U_\infty}{nD}$
  - Blade pitch, $\beta_{0.75} = 15.9^\circ$ to 35.6°
- Approximately 100 hours of testing

$\beta_{0.75R}$	No WT	J=0.3	J=0.4	J=0.5	J=0.6	J=0.7	J=0.8	J=0.9	J=1.0	J=1.1	J=1.2	J=1.3	J=1.4
15.9^o	X	X	X	X									
17.4^o	X	X	X	X	X								
19.2^o	X	X	X	X	X	X							
20.9^o	X	X	X	X	X	X	X						
22.5^o	X		X	X	X	X	X	X					
24.2^o	X		X	X	X	X	X	X	X				
25.8^o	X		X	X	X	X	X	X	X	X			
27.3^o	X		X	X	X	X	X	X	X	X	X		
28.9^o	X			X	X	X	X	X	X	X	X	X	
30.5^o	X			X	X	X	X	X	X	X	X	X	X
32.2^o	X			X	X	X	X	X	X	X	X	X	X
33.9^o	X			X	X	X	X	X	X	X	X	X	X
35.6^o	X			X	X	X	X	X	X	X	X	X	X

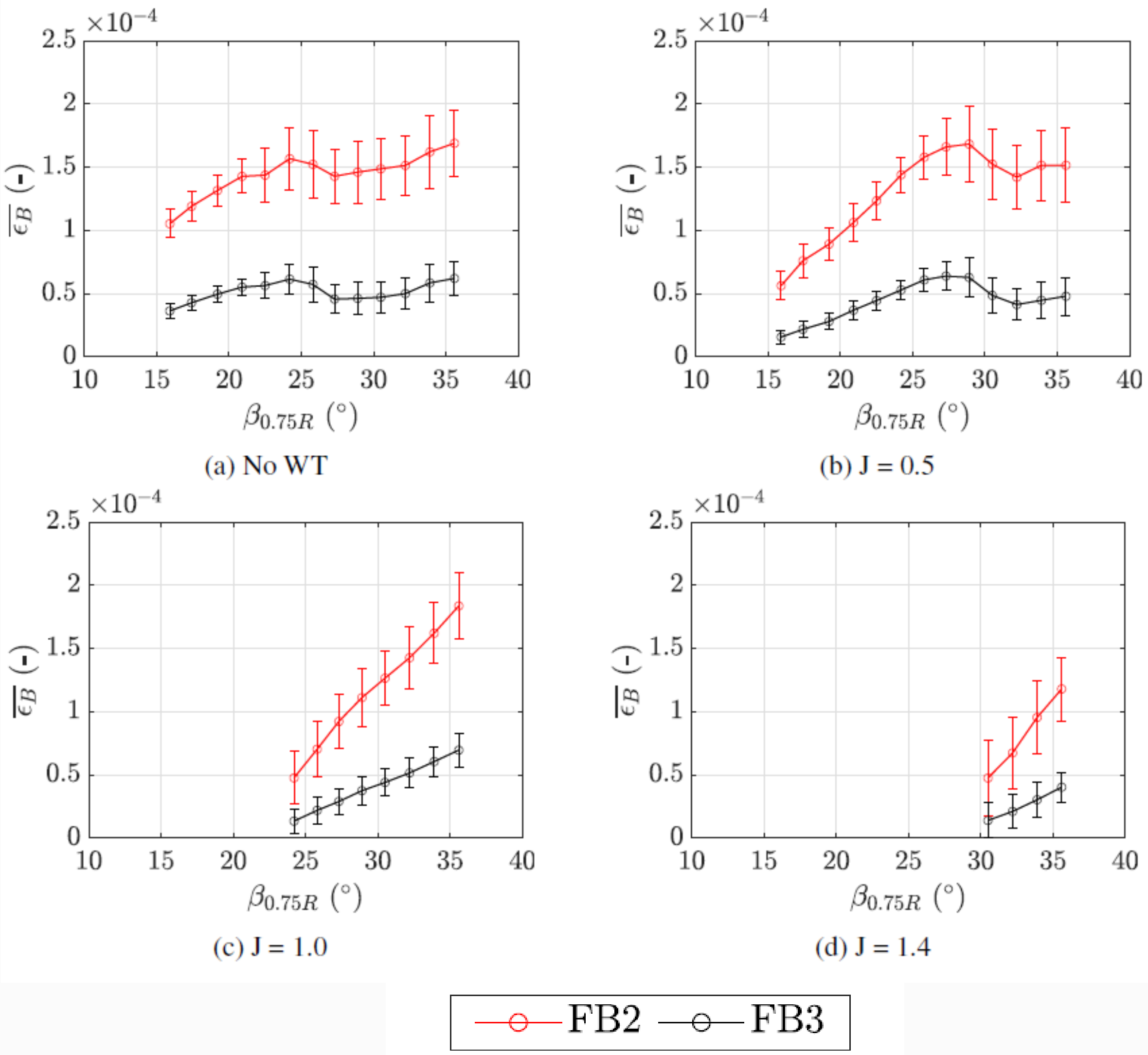
Wind Tunnel Velocity Reference

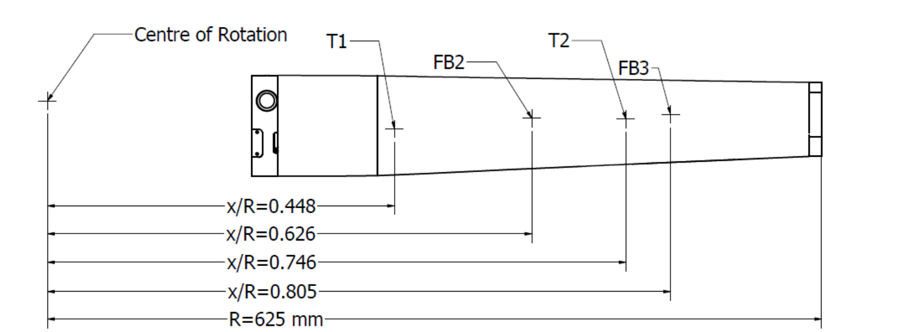
- Closed return wind tunnel
- Max U_∞ = 70 m/s, empty test section, $J = \frac{U_\infty}{nD}$
- Propeller induces velocity around the loop
- Calibration of contraction ring to set wind speed
- Becomes a stage where the UKNRR drives the wind tunnel flow





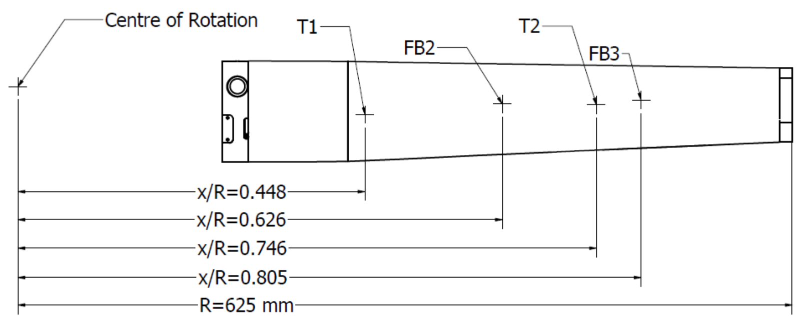
Results – Strain Gauge

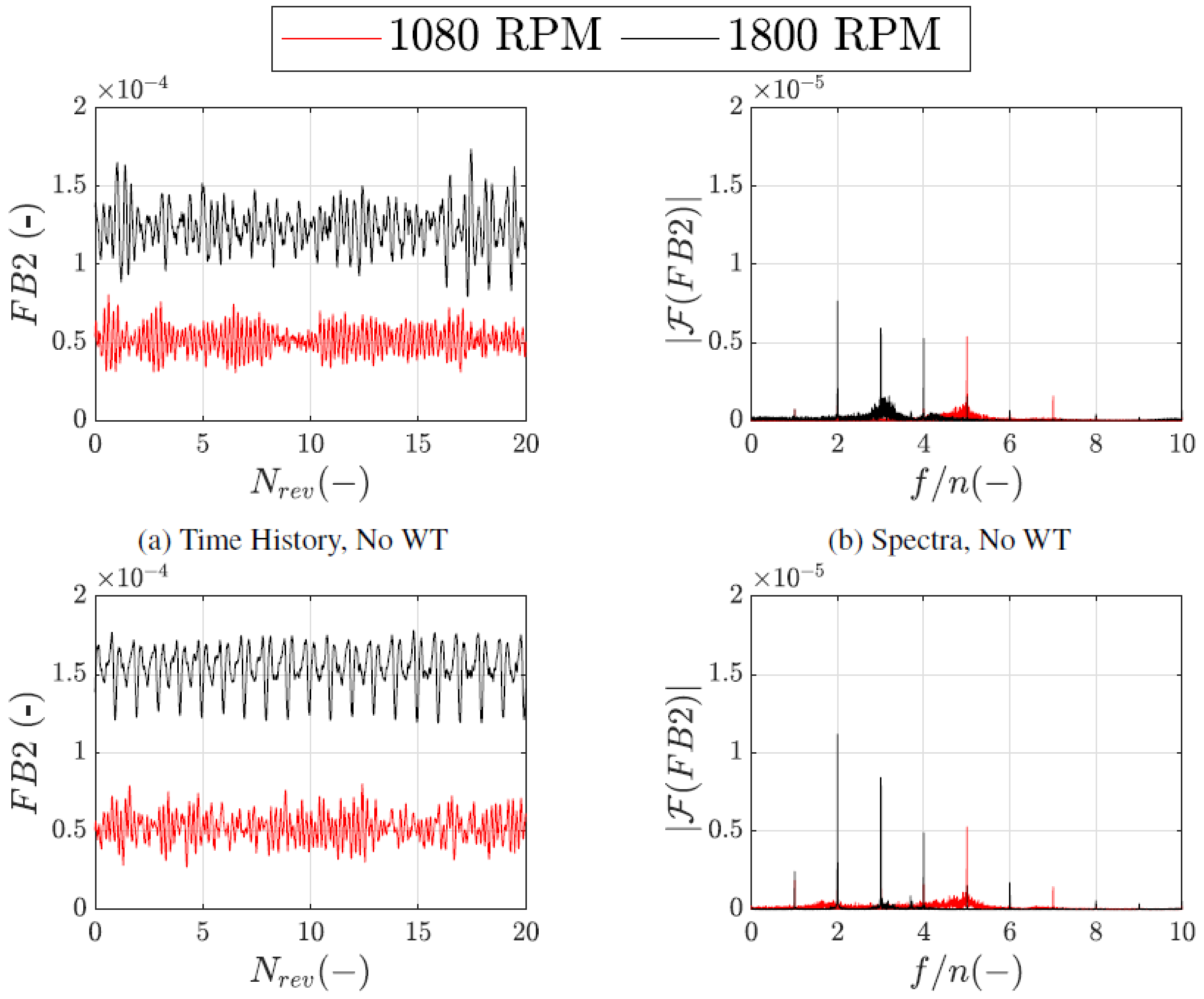




- Ω = 1080 RPM
- **Compensated strain** $\overline{\epsilon_B} = \epsilon_B \frac{\bar{\rho}}{\rho}\left(\frac{\bar{\Omega}}{\Omega}\right)^2$
  - $\bar{\rho} = 1.225\ \frac{kg}{m^3}$
  - $\bar{\Omega} = 1800\ RPM$
  - Equivalent dynamic pressure
- Delay in stall onset with increased J
- Stall indicators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

Results – Strain Gauge

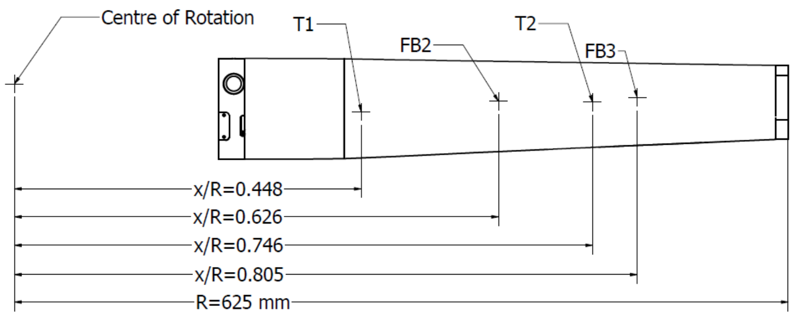


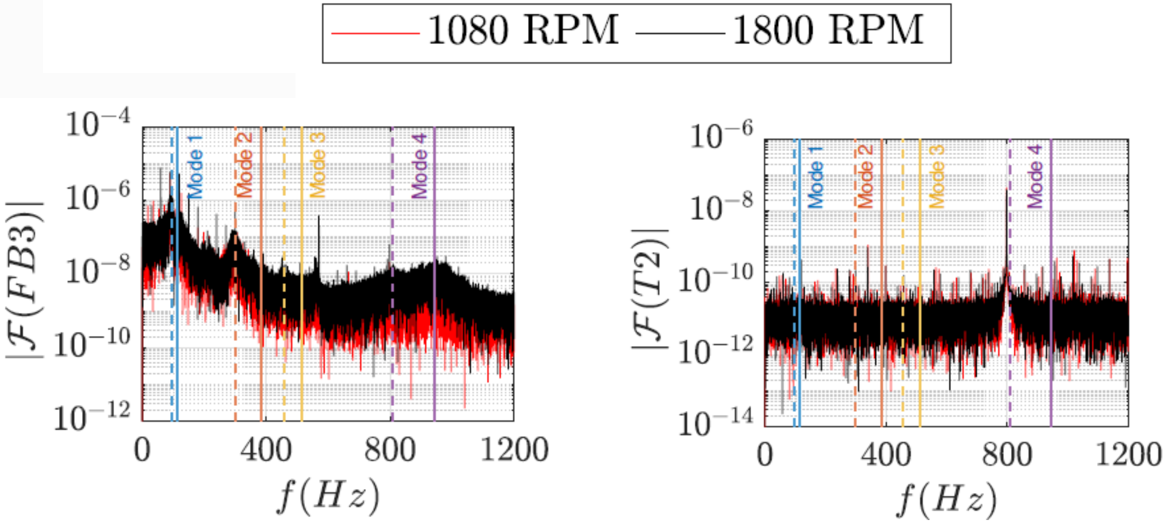


(a) Time History, No WT
(b) Spectra, No WT
(c) Time History, J = 0.5
(d) Spectra, J = 0.5

- $\beta_{0.75} = 30.5^{\circ}$
- 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
  - 1800 RPM 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.

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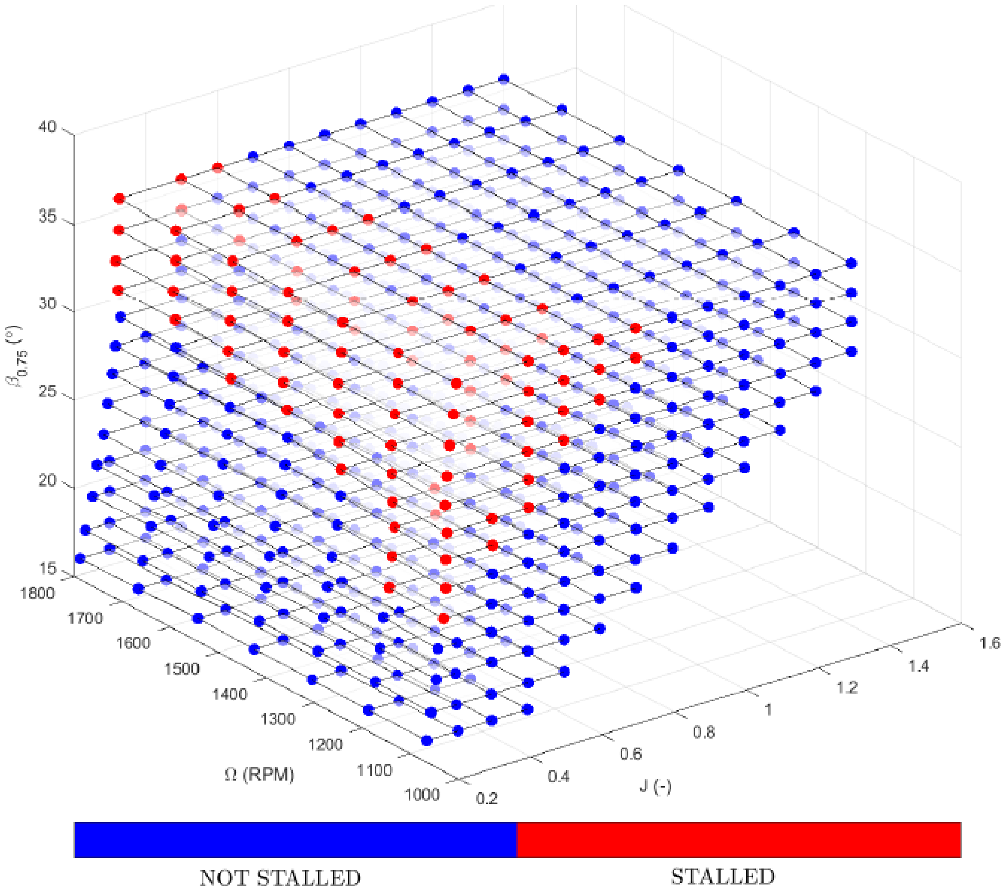
Results - Stall Boundary Criteria

- **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.



Conclusions

- A criteria to detect stall onset using strain gauges was developed.
- Flap bending bridges are shown to be reliable in detecting stall onset.
- Criteria in agreement with aerodynamic performance measurements.
- Blade modes can be clearly identified.

Thank you for your attention

Any Questions?

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