Unsteady structural behaviour of small wind turbine blades

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Small wind turbine technology

	Small wind turbines	Large wind turbines
Rotor diameter	< 16 m*	90 - 120 m
Power output	< 50 kW*	1.8 - 3 MW
Reynolds number	8,400 – 500,000	> 500,000
Rotor speed	200-400 rpm	20-50 rpm
Yaw control	Passive control via tailfin	Yaw drive with input from anemometer and wind vane
Primary use	Off-grid generation Wind/diesel hybrid system	Commercial scale generation (wind farm)
Generation site	Located close to load (suboptimal wind resource)	Located in optimum wind resource
Wind regime	Lower mean wind speed High turbulence	Higher mean wind speed Low turbulence
Capacity factor	5-30%	20-45%

*IEC 61400-2 – 2013

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Project aim

- Unsteady structural loads on small wind turbine blades:
  - Classifying
  - Simulating
  - Experimentally measuring
- Ramifications on structural behaviour and fatigue life
- Wind turbines are fatigue critical
- Established methodologies for large wind turbines
- Limited research in small wind turbine field

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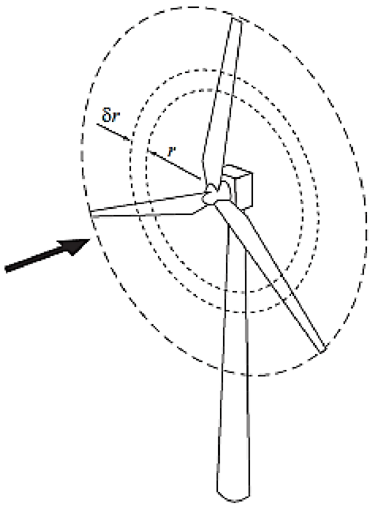
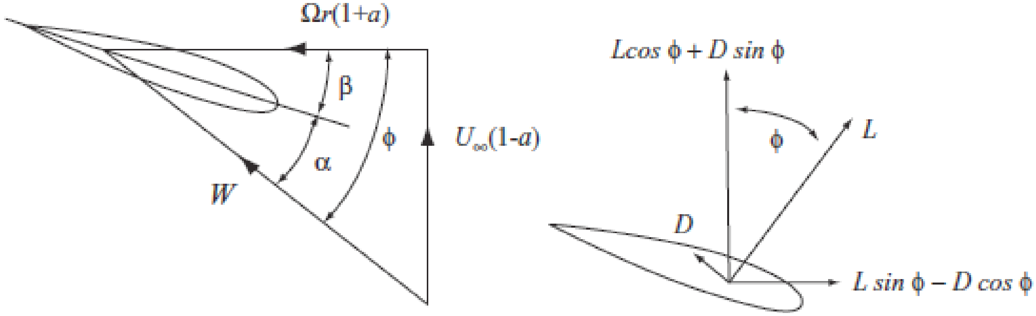
Blade element momentum theory

- Classical blade element momentum theory:
  - Conservation of momentum
  - 2D blade theory
- Modification (unsteady):
  - Prandtl tip loss factor
  - Yaw misalignment
  - Wind shear effects
  - Blade/tower influence
  - Dynamic stall
  - Dynamic inflow/wake





Burton (2001)

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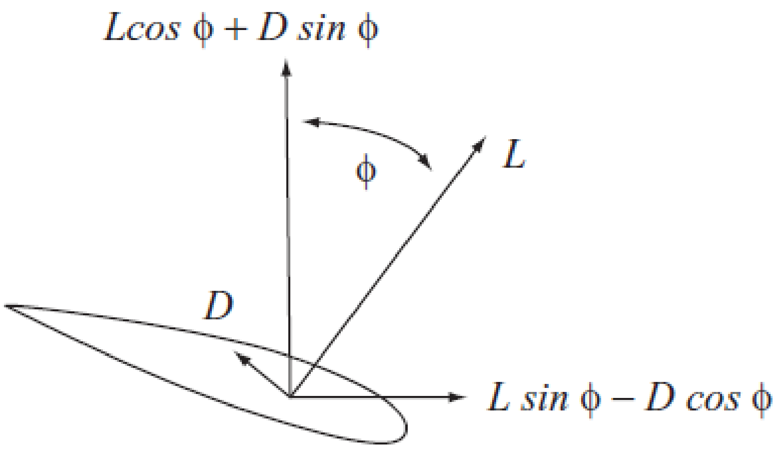
Structural load cases

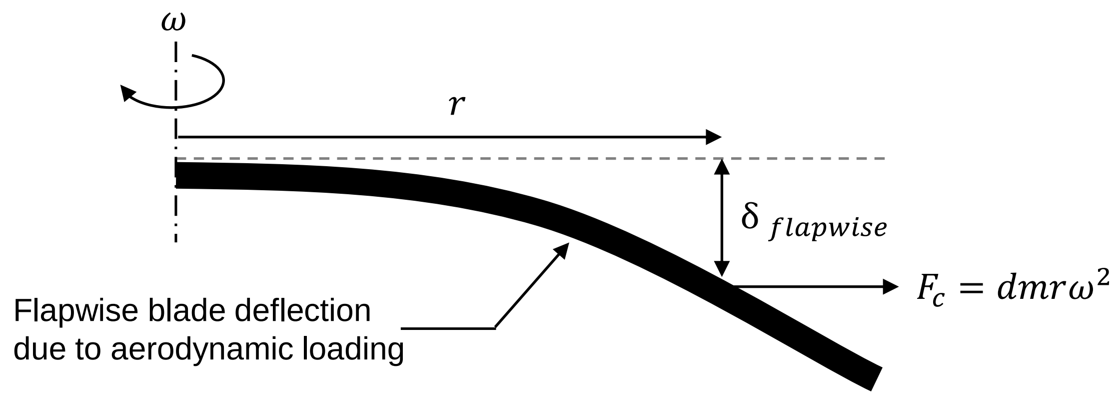
- Aerodynamic
- Gravitational



Burton (2001)

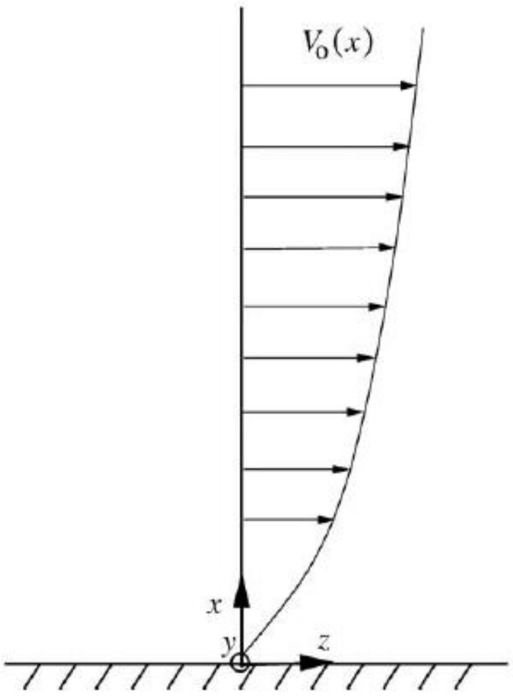
Structural load cases

- Aerodynamic
- Gravitational
- Centrifugal



Structural load cases

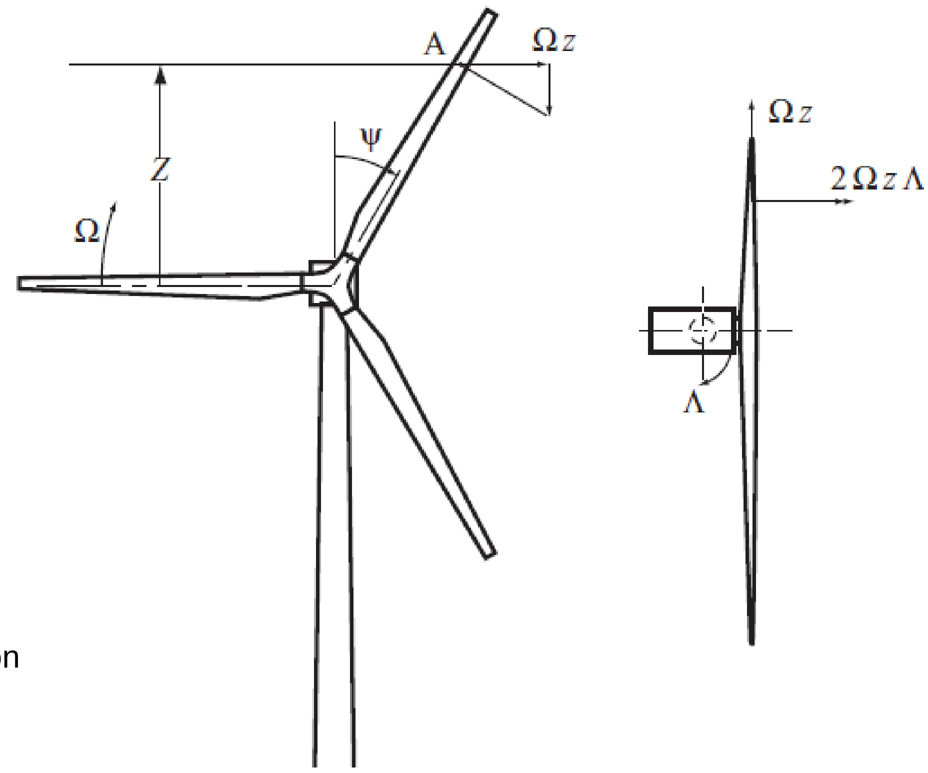
- Aerodynamic
- Gravitational
- Centrifugal
- Wind shear



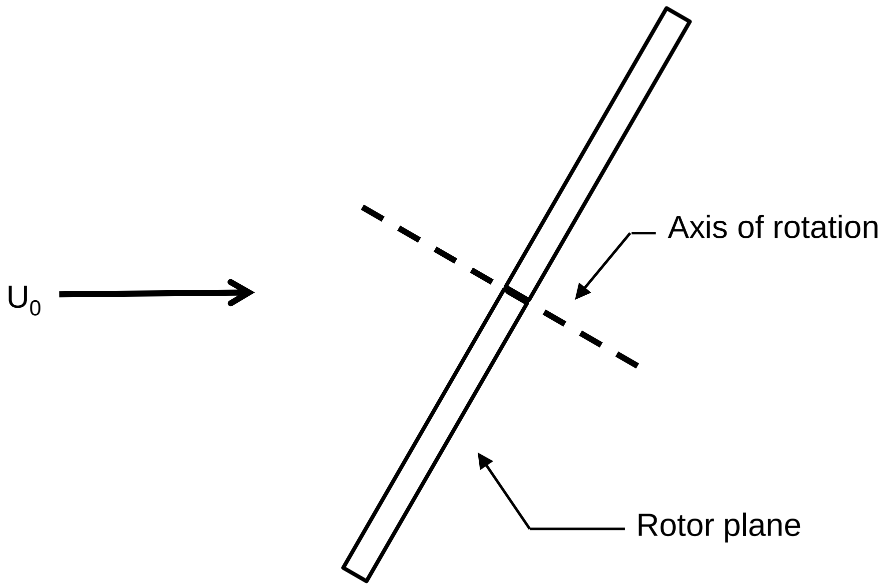
Hansen (2008)

Structural load cases

- Aerodynamic
- Gravitational
- Centrifugal
- Wind shear
- Yaw misalignment
- Gyroscopic

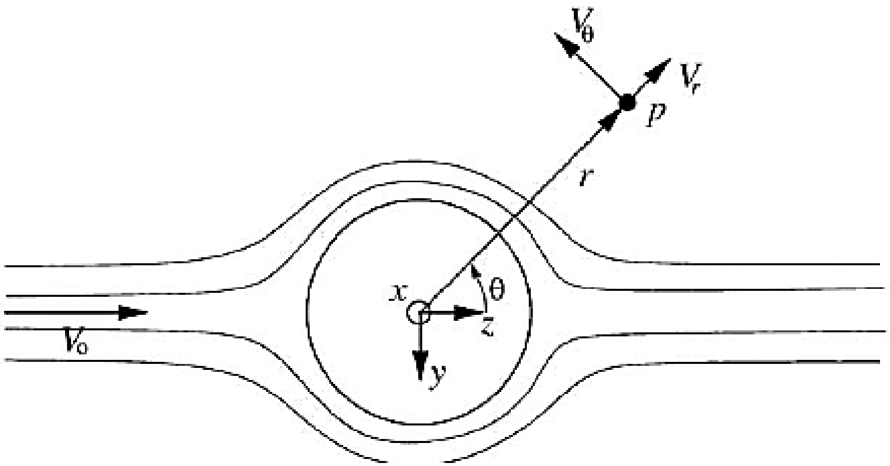


Burton (2001)



Structural load cases

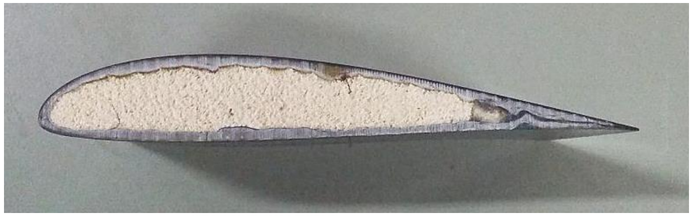
- Aerodynamic
- Gravitational
- Centrifugal
- Wind shear
- Yaw misalignment
- Gyroscopic
- Blade/tower interaction



Hansen (2008)

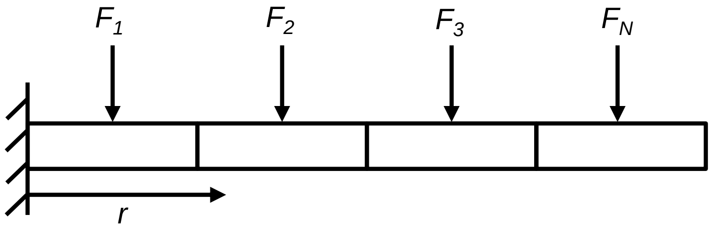
Blade design

- Length: 2.5 m
- Mass: 6.5 kg
- Constructed from GFRP
- No spar (internal foam core section)
- SD7062 aerofoil
- High stiffness in lead-lag direction
- Natural frequency ~7 hz, out of operating range!



Structural model: simple beam

- Euler-Bernoulli beam theory:
  - Blade considered as a series of *n* elements
  - Stiffness (*EI* [Nm^2]) & mass (dM [kg/m])
  - Small deflections, constant radius of curvature
- Centrifugal stiffening effects
- Difficulties with convergence due to high ω_{rot} term
- Deflections, fibre stress, and resonant frequencies obtained
- Computationally fast to implement



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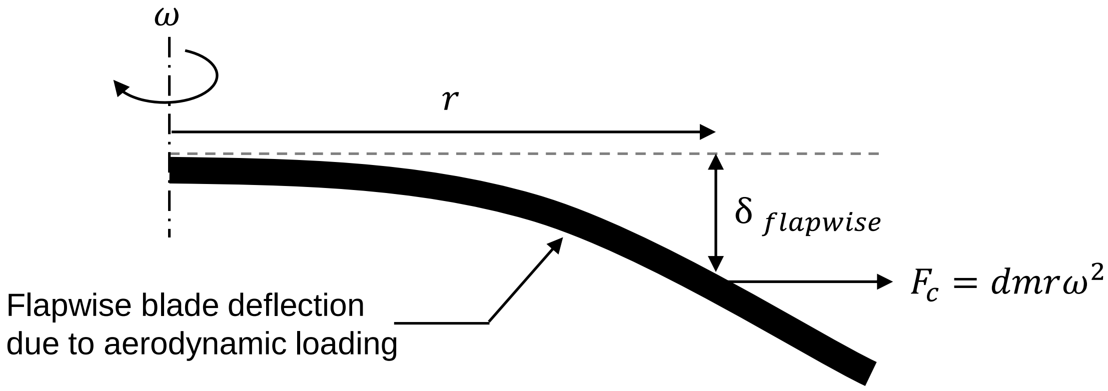
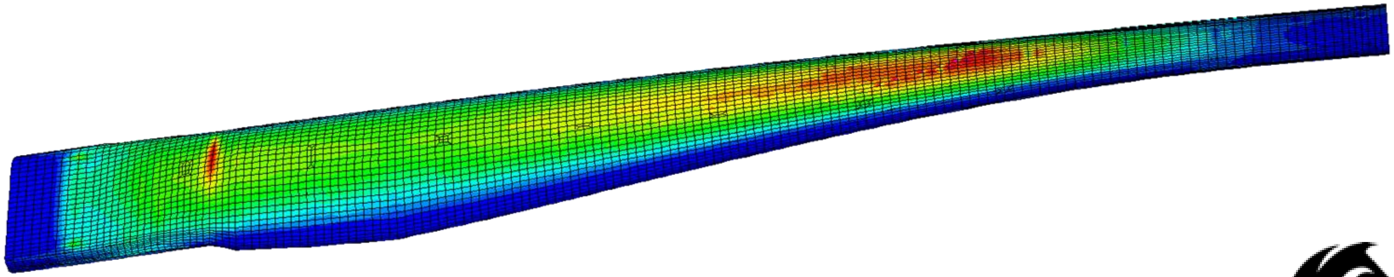


Structural model: finite element

- 1. Simple 2D plate model:
  - Isotropic material property set
  - Lack of internal foam member
- 2. Full composite model:
  - Anisotropic material set (GFRP)
  - Inclusion of internal foam section as 3D brick elements
  - Calibrated with physical blade to high degree of accuracy
- Loads applied from unsteady BEM algorithm
- Centrifugal effects accounted for via a non-linear solve



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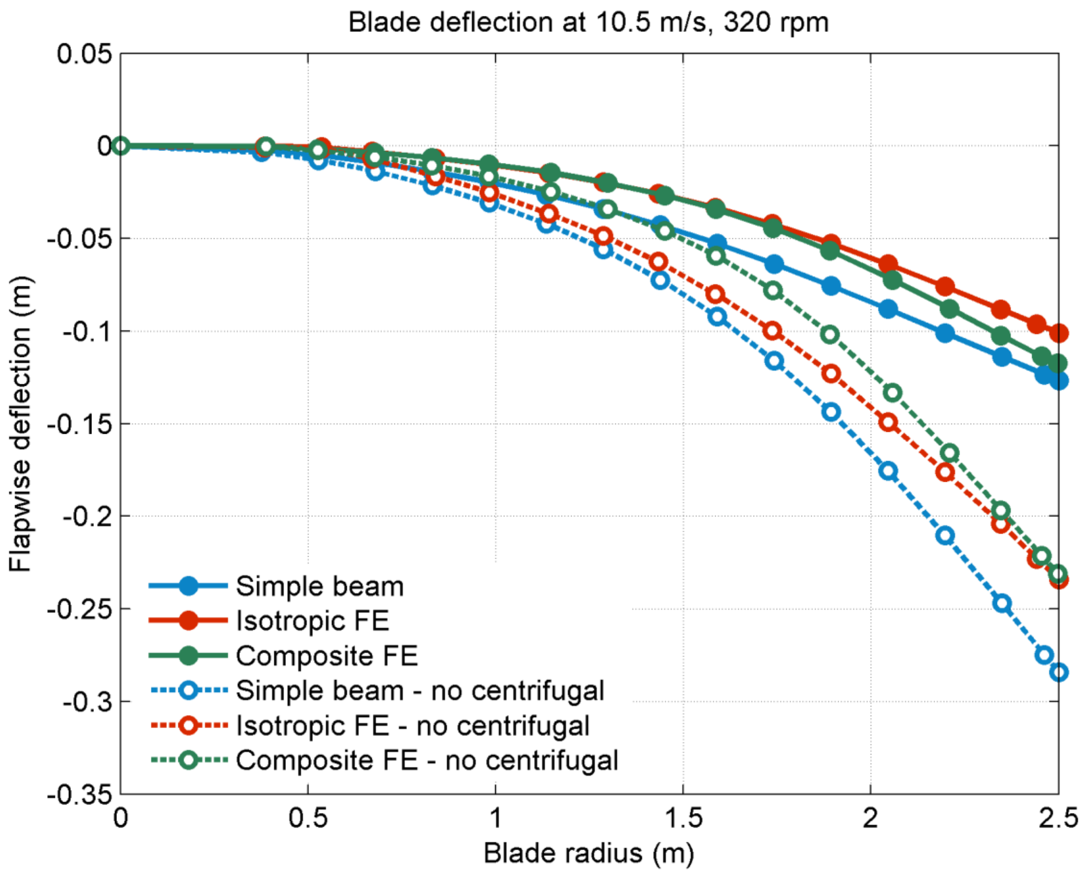
Structural model: results

- Three structural models were compared
- Composite FE model has high accuracy with physical blade
- Simple beam over predicts deflection and stress (~ span/25)
- Difficulties with convergence when considering centrifugal effects for simple beam (non-linear effects)

Method	Lead-lag deflection (mm)	Flapwise deflection (mm)	Maximum stress (MPa)	Normalised comp. time
Composite FE	17	118	32	25,741
Isotropic FE	15	101	23	6,422
Euler	20	127	53	1

Structural model: results

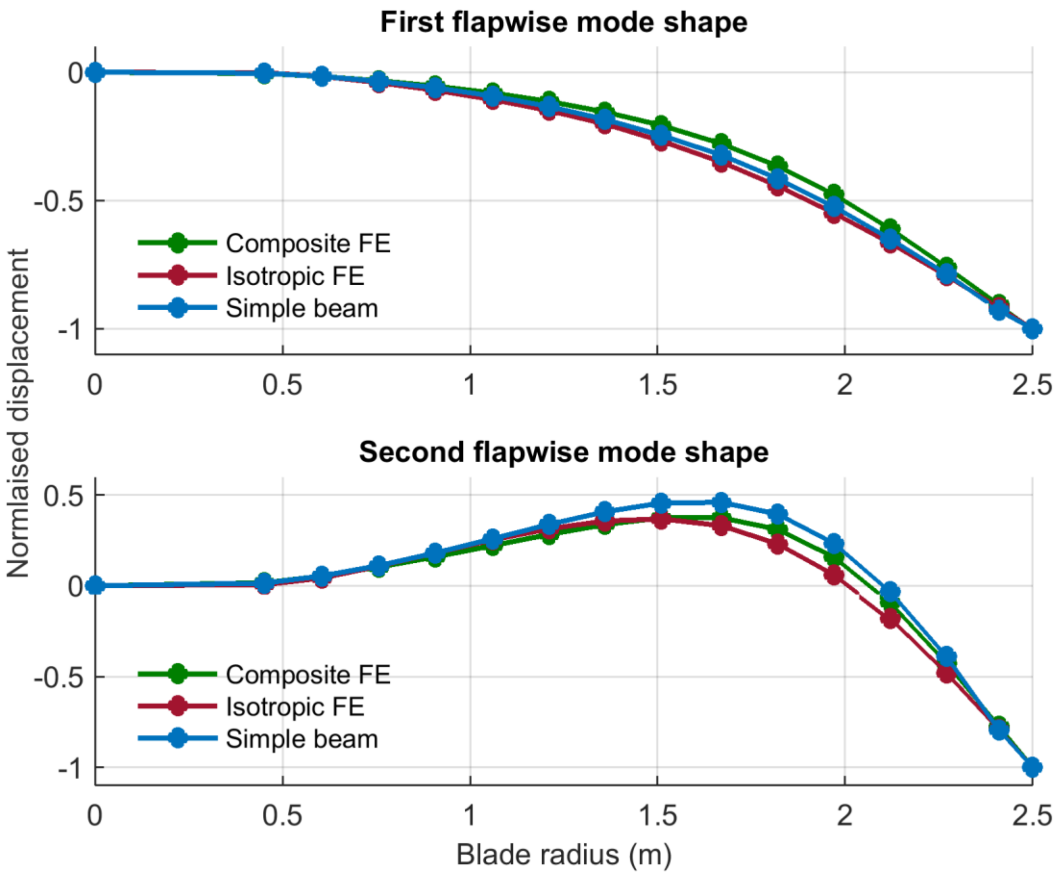


Structural model: results

- Natural frequencies and mode shapes predicted
- Good general agreement ±10%
- Outside operating range (~5 Hz at operating speed)
- Centrifugal stiffening effects increase the natural frequency

Method	First mode (Hz)	Second mode (Hz)
Physical blade	7.41	17.62
Composite FE	8.09 (9.18%)	19.65 (11.52%)
Isotropic FE	6.85 (-7.56%)	19.72 (11.92%)
Euler	6.52 (-12.01%)	21.04 (19.41%)

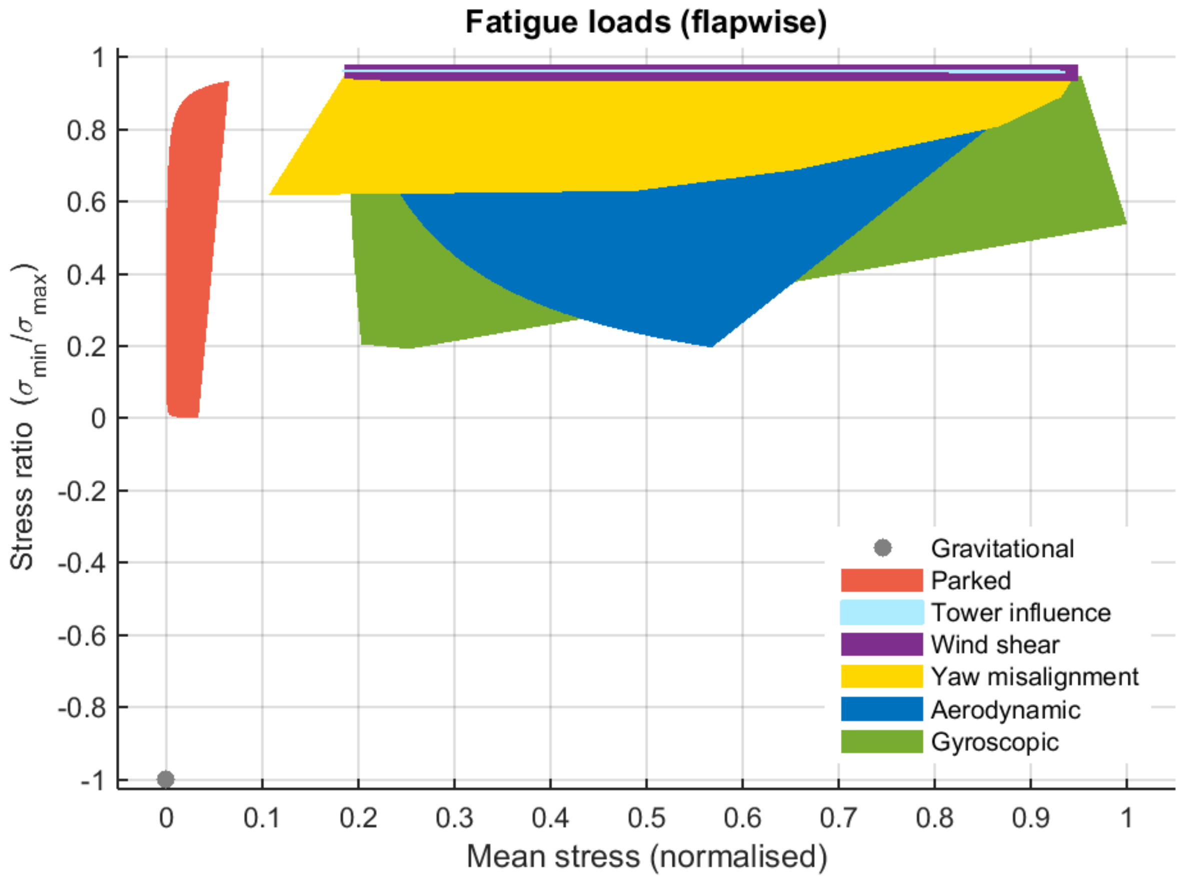
Mode shapes


First flapwise mode shape
0
-0.5
-1
0
0.5
1
1.5
2
2.5
Composite FE
Isotropic FE
Simple beam
Normlaised displacement
Second flapwise mode shape
0.5
0
-0.5
-1
0
0.5
1
1.5
2
2.5
Composite FE
Isotropic FE
Simple beam
Blade radius (m)

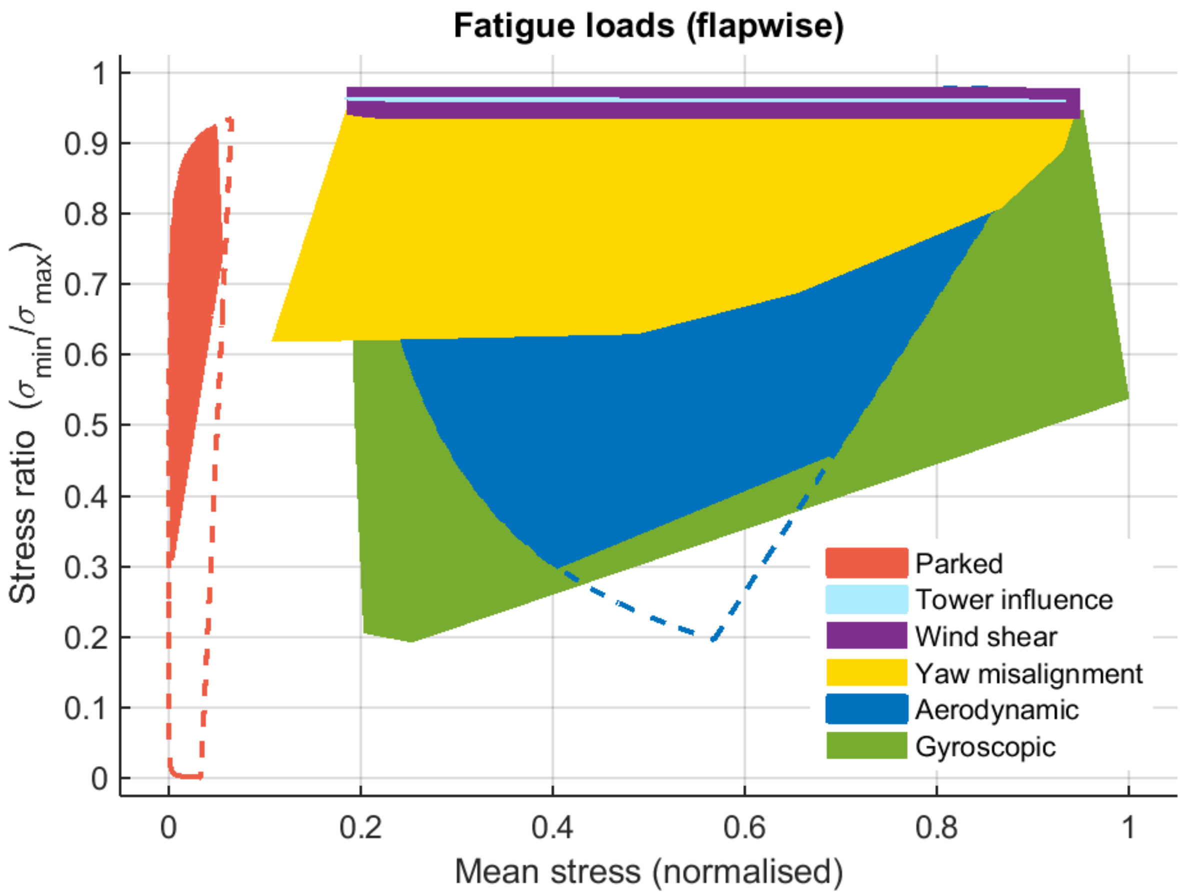
Putting it all together

- Development of aerodynamic and structural model
- Consider small wind turbine operation within the following ranges:
  - Inlet wind speed 5-12 ms^{-1}
  - Rotor speeds: 120-320 rpm
  - Yaw error: 0-60 °
  - Yaw rate: 0-60 ° /sec
  - Wind shear factor: 0.0-0.3
  - Blade/tower interaction
  - Parked loading during shutdown

Putting it all together



Putting it all together

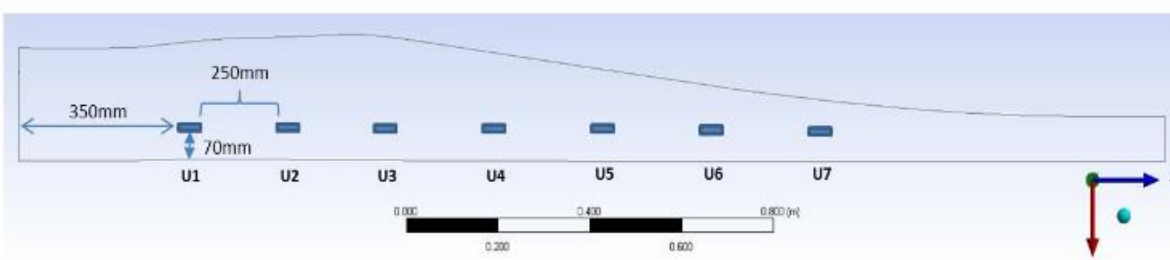


Preliminary conclusions

- Gravitational, wind shear, tower/blade interaction, and yaw error are less significant
- Gyroscopic loads:
  - Encompass most load cases
  - Worst case fatigue load
  - Highest ultimate load
- Ramifications for passively controlled turbines
- Centrifugal stiffening effects are significant
- Simple beam theory is computationally fast, at reduced accuracy

Future work: experimental validation

- Arduino measurement system:
  - Blade strain
  - Wind speed and direction
  - Turbine heading and yaw rate
  - Turbine rpm and generator power
- Measurement campaigns to record blade response
- Validation of simulated blade loads with experimental data
- Recommendations for improved blade structural design and fatigue life



Questions?

Acknowledgements

Work in this presentation was supported by an Australian Postgraduate Award (APA) and ARC DP grant (DP110103938)

References

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