System Engineering

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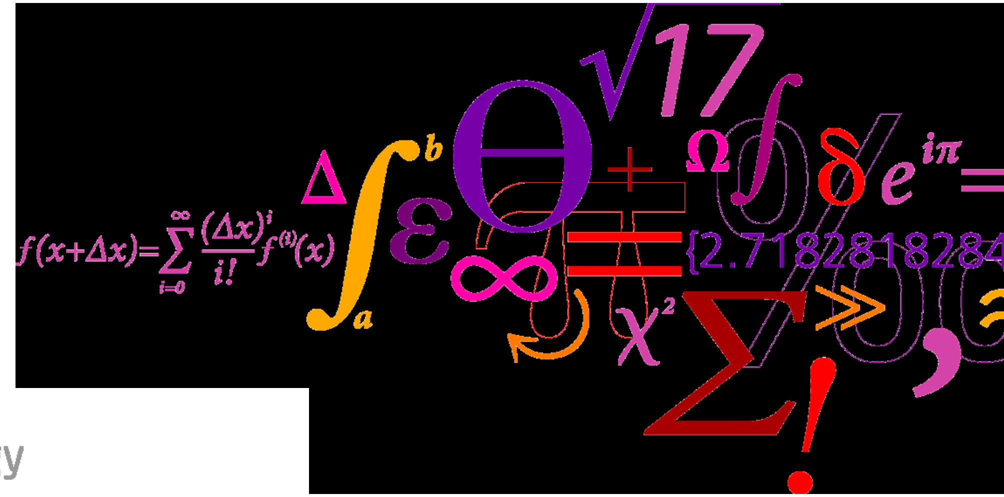
Wind Energy Division

Risø DTU



System Engineering

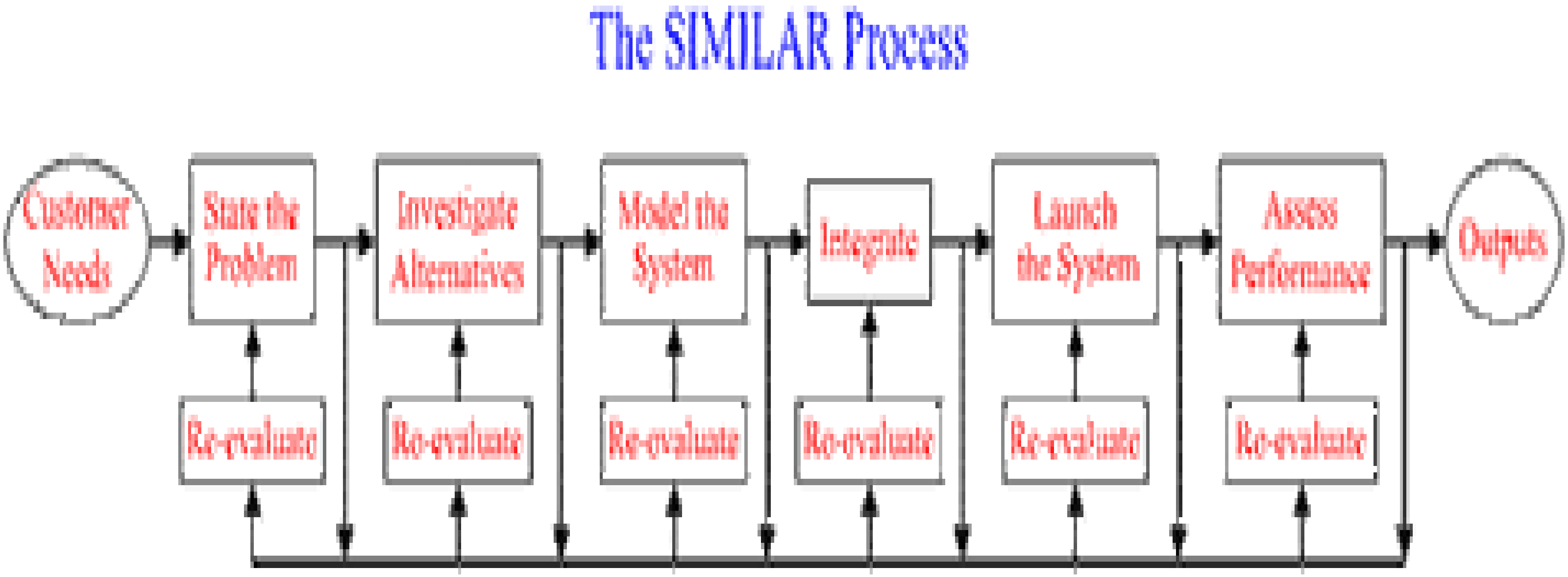


Figure 1. The Systems Engineering Process from A. T. Bahill and B. Gissing, Re-evaluating systems engineering concepts using systems thinking, *IEEE Transaction on Systems, Man and Cybernetics, Part C: Applications and Reviews*, **28** (4), 516-527, 1998.

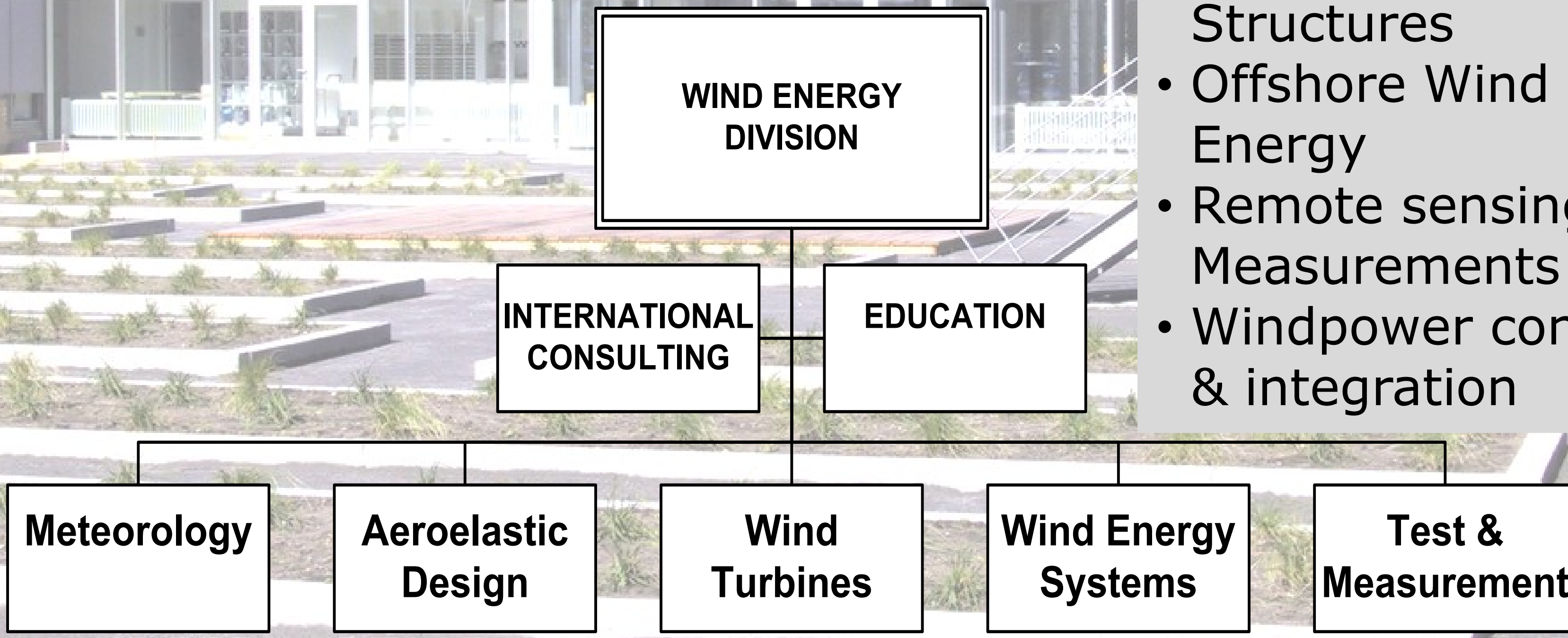
Risø DTU mission:

Quality – Relevance – Impact

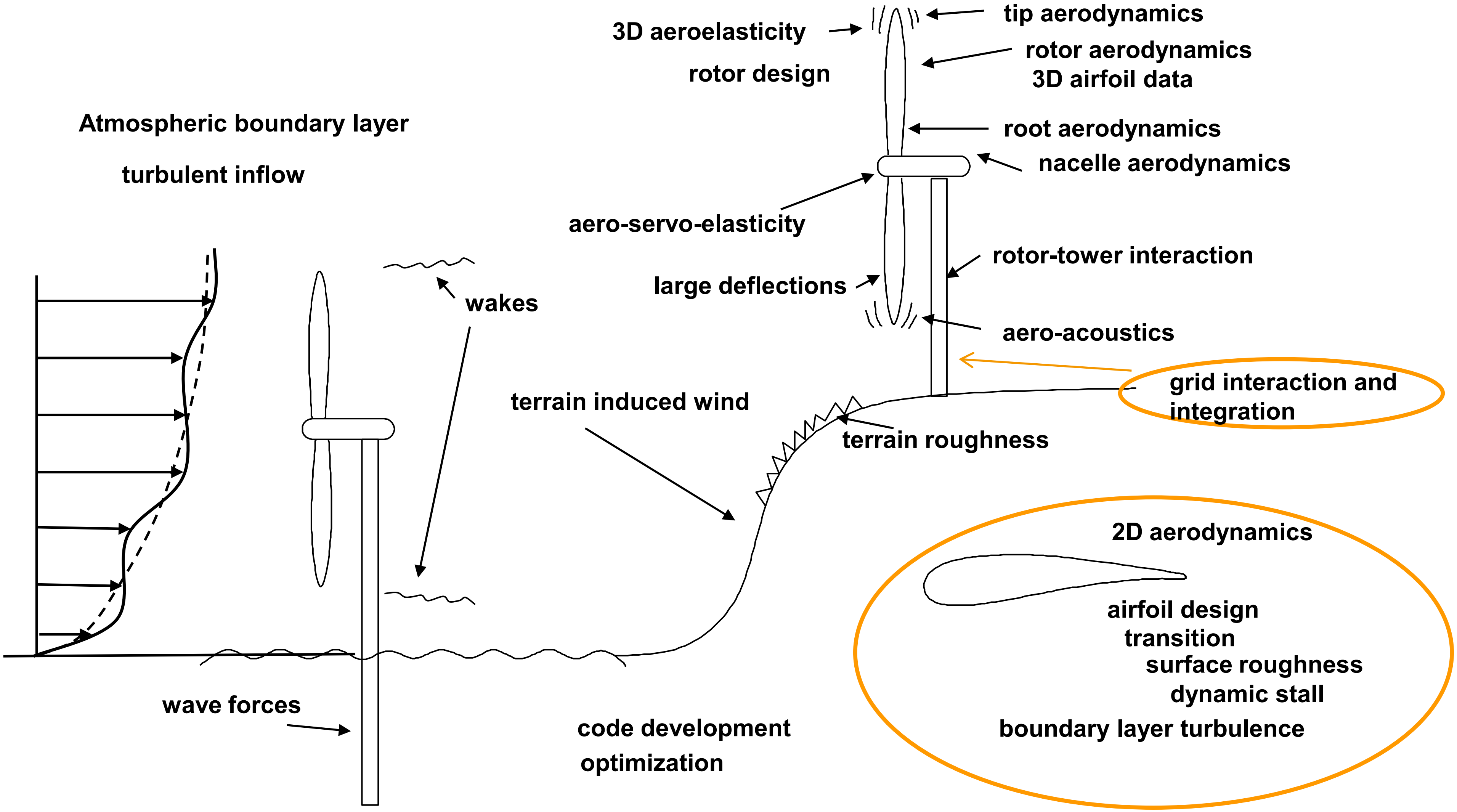
Wind Energy Division - Risø DTU
Technical University of Denmark

Research Themes:

- Windpower Meteorology
- Aeroelastic design methods
- Wind Turbine Structures
- Offshore Wind Energy
- Remote sensing & Measurements
- Windpower control & integration



Wind turbine aerodynamics and aeroelasticity - optimisation



Aeroelastic codes and simulations

Aeroelastic codes for time simulations:

- **FLEX4**
- **BLADED**
- **FAST**
- **HAWC2**

- simulations in real time or faster

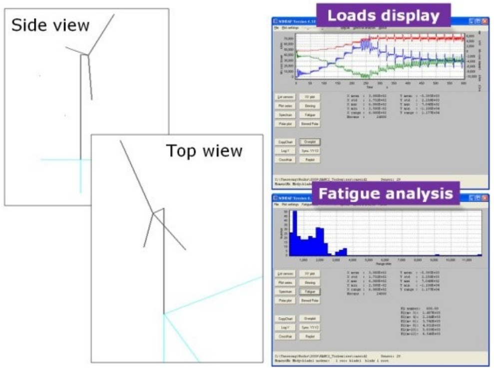
Engineering sub-models for simulation of:

- yawed flow
- dynamic stall
- unsteady blade aerodynamics
- unsteady inflow
- tip loss
- tower shadow
- wakes from neighboring turbines
- simulation of turbulent inflow
- control

HAWC2 – Risø DTU's code for wind turbine load and response

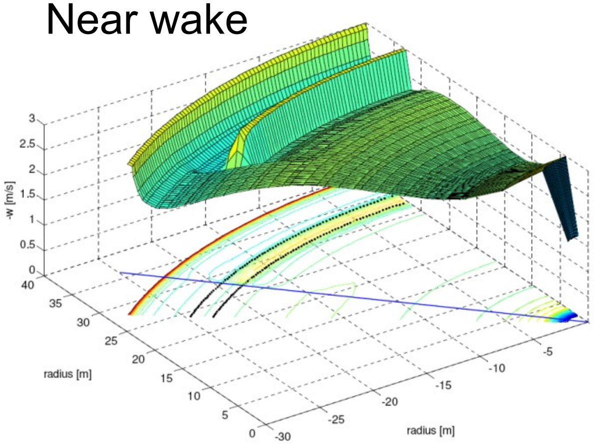
- **A tool for simulation of wind turbine load & response in time domain.**
  - Normal onshore turbines; 3B, 2B, pitch control, (active) stall
  - Offshore turbines (monopiles, tripods, jackets)
  - Floating turbines (HYWIND concept for now, later… Sway, Poseidon).
- Based on a multibody formulation, which gives great flexibility

- **It is a knowledge platform!**
  - New research/models are continuously implemented and updated.
  - Core is closed source. E.g. Structure, aerodynamics, hydrodynamics, solver…
  - Submodels are open-source. E.g. water kinematics, standard controllers, generator models.

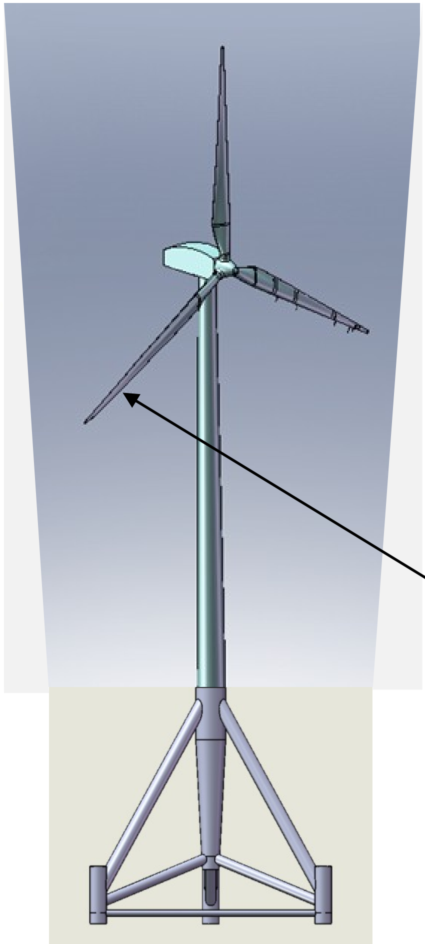


HAWC2: Numerical platform for time simulation studies of complex wind turbine loading.

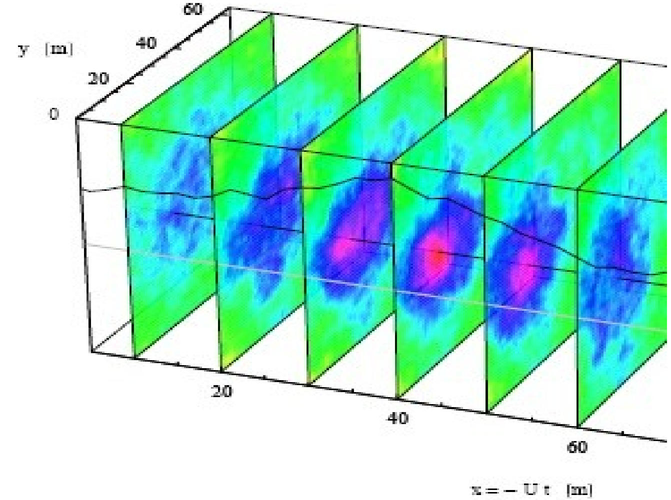
Near wake

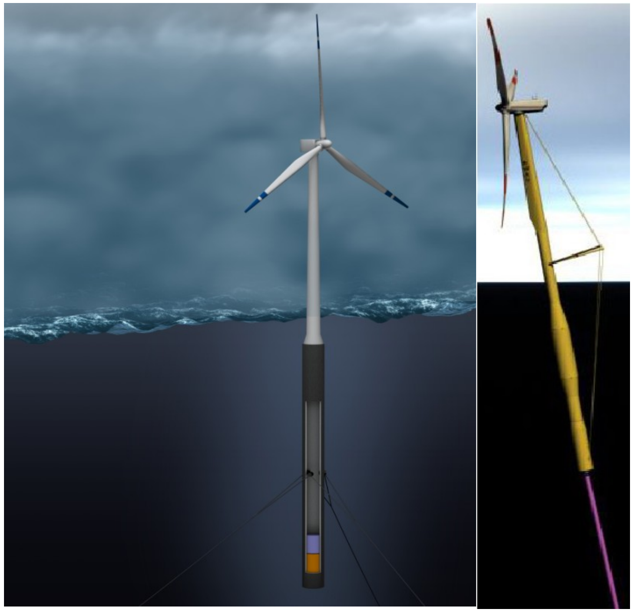


Large deflections



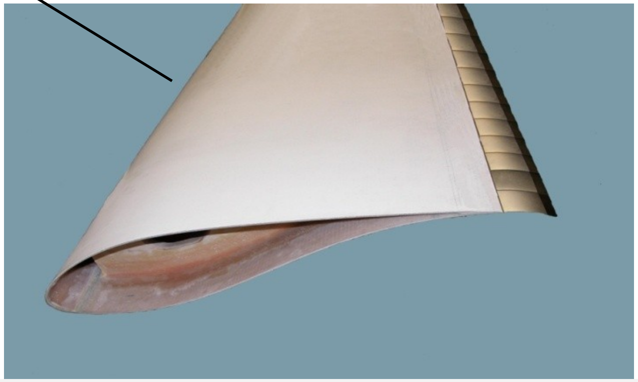
Meandering wake





Offshore structures
- and floating

Distributed control



Components in System Engineering at Risø

- HAWC2 aeroelastic optimisation
- HAWCStab2: combined aeroelastic and control design
- Airfoil optimisation (including noise)
- Blade design including structure, noise
- Topology optimisation of wind farms (Site specific design)

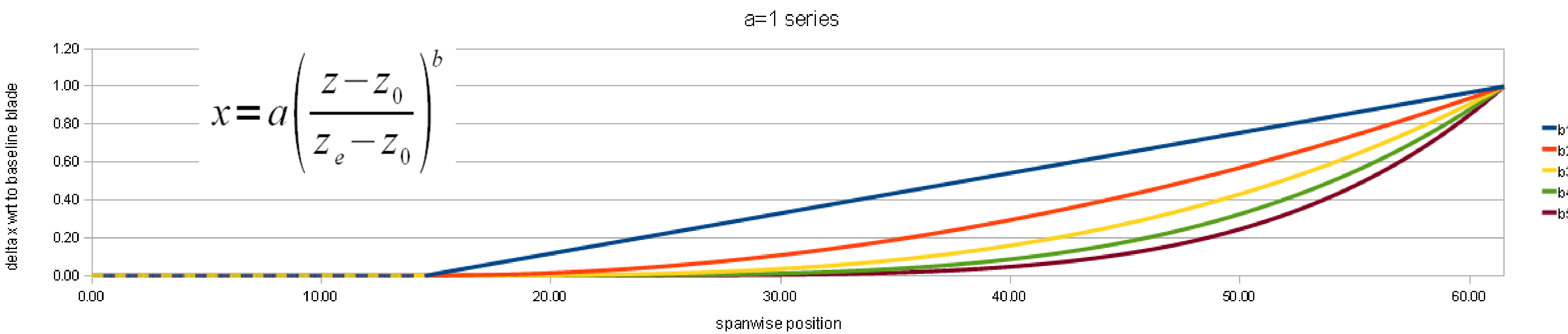
In progress:

- (Integrated design of offshore support structure and turbine)
- (Turbine, wind farm and grid-interaction)

Optimisation of blade pre-sweep

Analysis of various pre-swept geometries and wind conditions

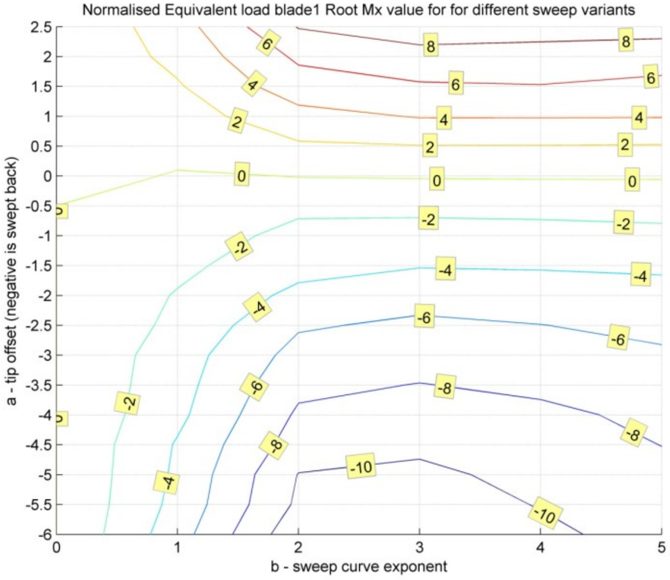
- 5 sweep curve exponents combined with
  24 tip offsets = 120 + 1 (ref.) blade variants
- Steady wind speeds (4..26 m/s, 1m/s steps)
- Turbulent wind speeds (4..26 m/s, 2m/s steps, 10 min series) same seed number, TI=0.18
- Total of 1573 simulations



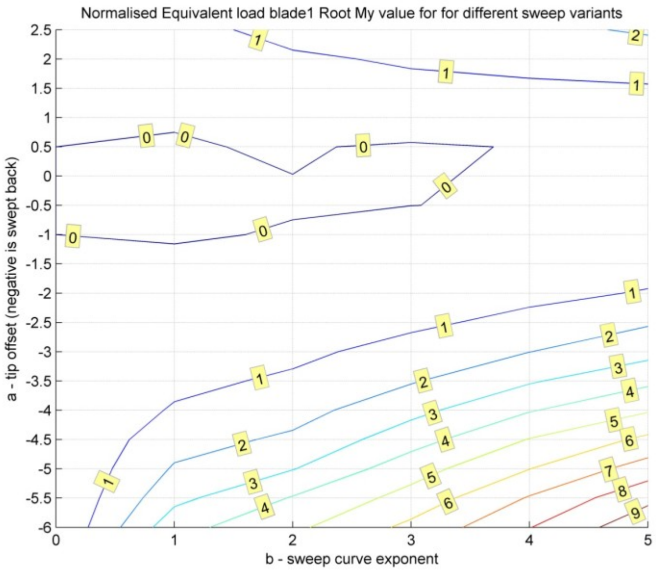
$$x = a\left(\frac{z - z_0}{z_e - z_0}\right)^b$$

Equivalent Loads (fatique)

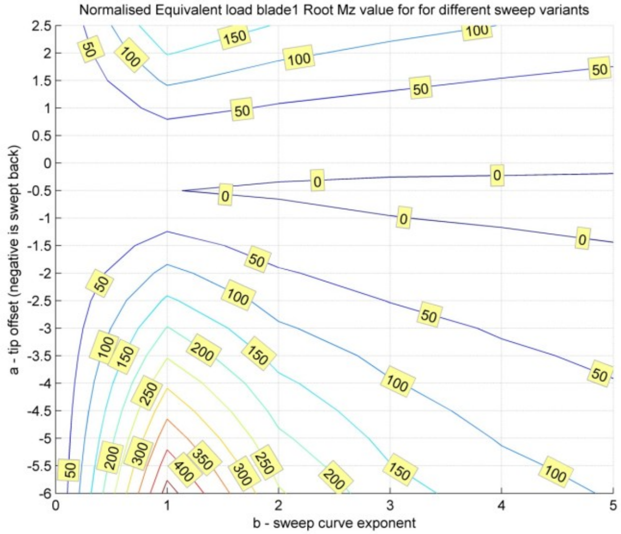
Flapwise



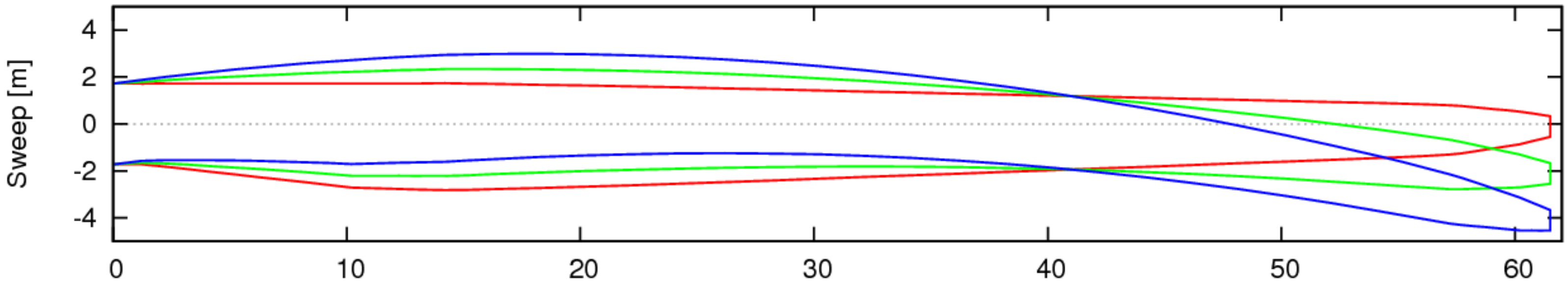
Edgewise



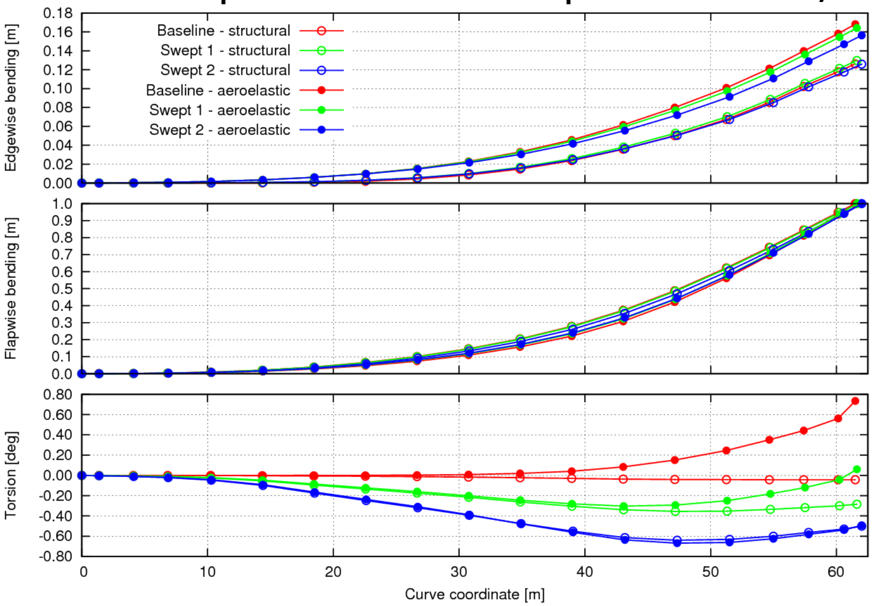
Torsion



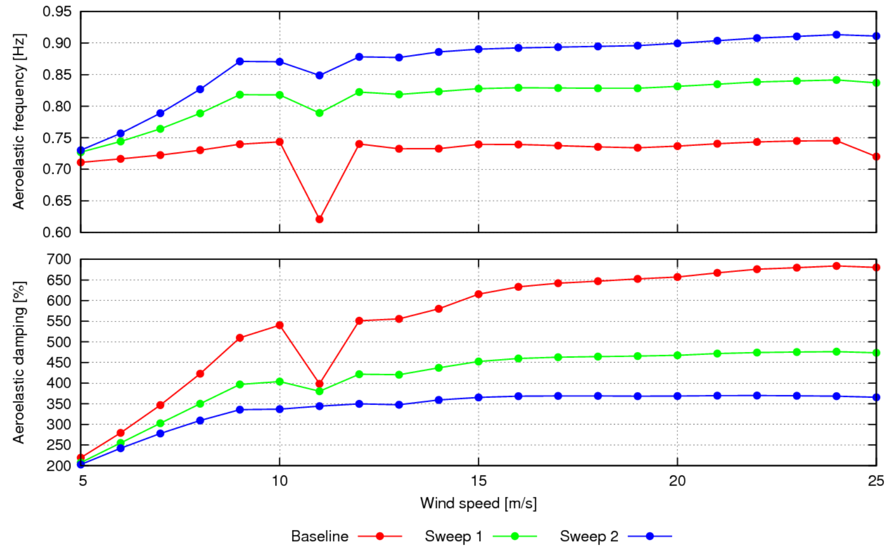
HAWCStab2 – Aeroservoelastic modal analysis
Example: Swept blades



First flapwise mode shapes at 12 m/s

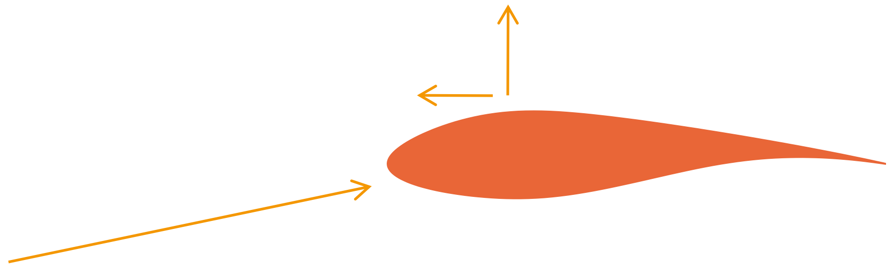


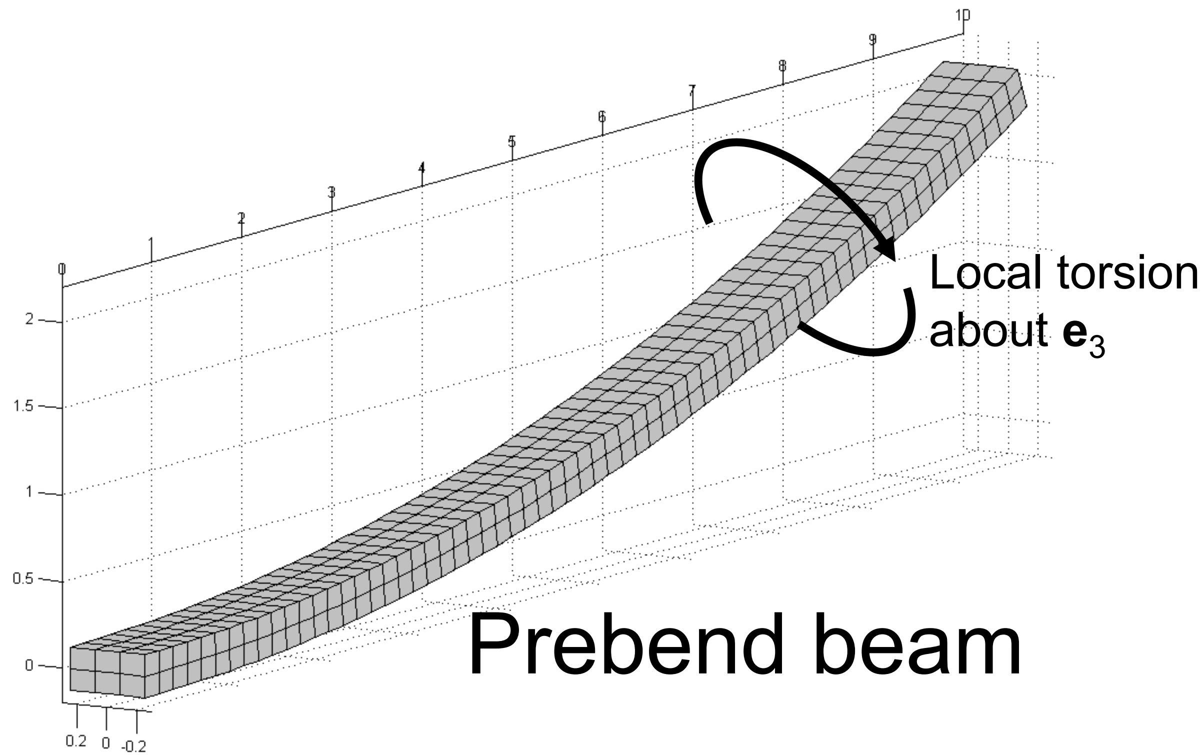
First flapwise frequencies and damping



Aeroelastic stability

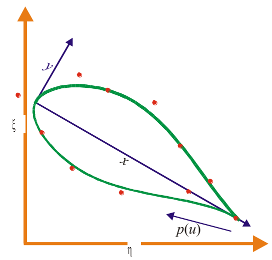
Forward pre-bending
increases edgewise stability

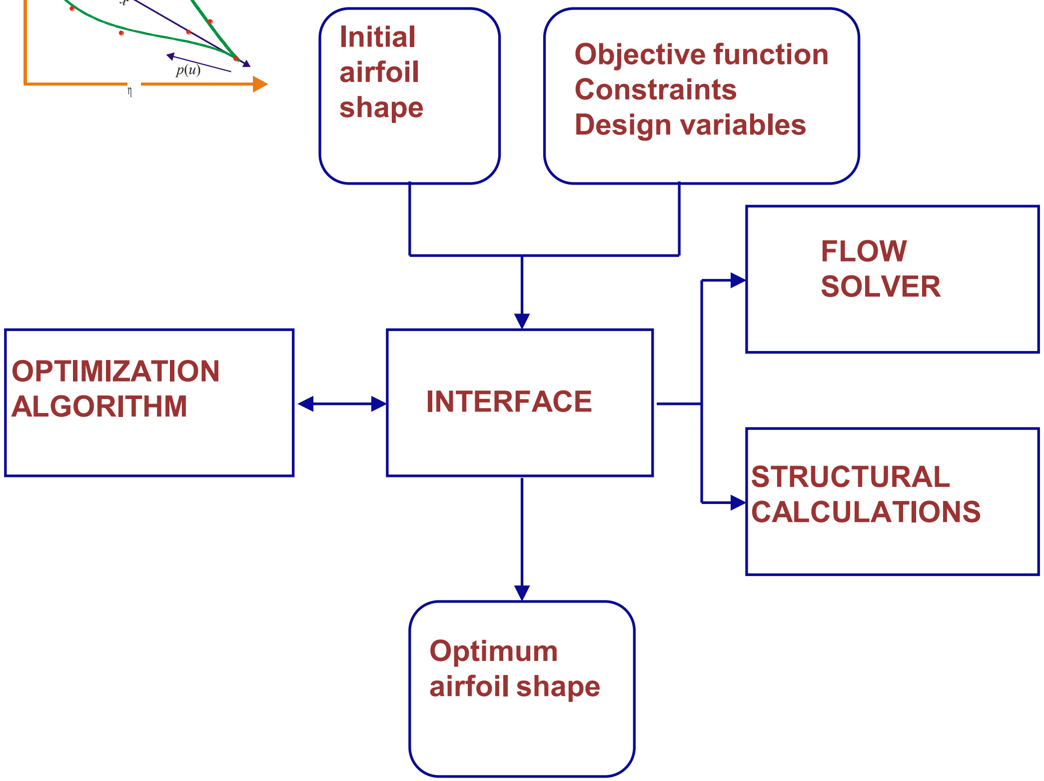


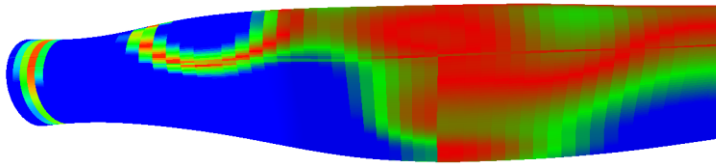


Airfoil optimisation: AirfoilOpt - flow chart

- A direct multipoint and interdisciplinary design tool
- An optimization algorithm coupled with a general 2D flow solver: XFOIL (or EllipSys2D)
- B-spline formulation of the 2D airfoil shape
- A Simplex optimizer – or other type of optimization algorthm
- Multiple angles of attack are analyzed
- Model of moment of inertia with shell thickness
- 3D tool with Cubic B-spline formulation of the 3D blade shape and rotor flow calculations

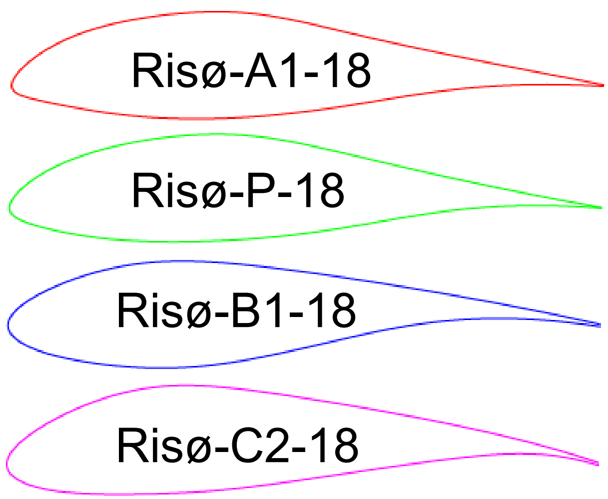






Airfoil design

- Several lessons have been learned from four airfoil series designed 1998 to 2007 (Risø-A1, Risø-P, Risø-B1 and Risø-C2) :
  1. Roughness insensitivity is very important
  2. High aerodynamic efficiency is very important
  3. Structural stiffness is important
  4. High compatibility is important
  5. Low noise is important
  6. High lift is important for some concepts



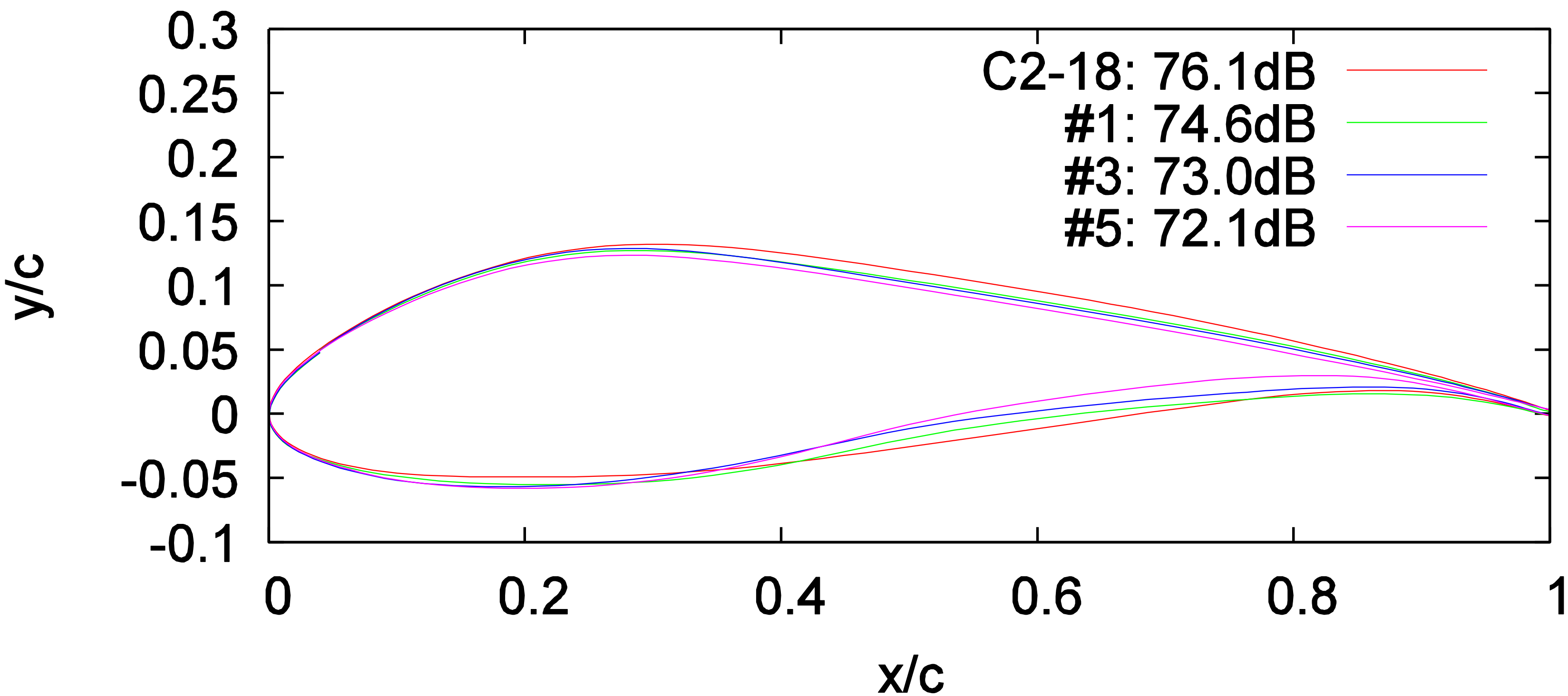
Designed for stall regulation

Designed for pitch regulation

Designed for pitch regulation variable speed

Designed for pitch regulation variable speed

New development: Noise (TNO model)

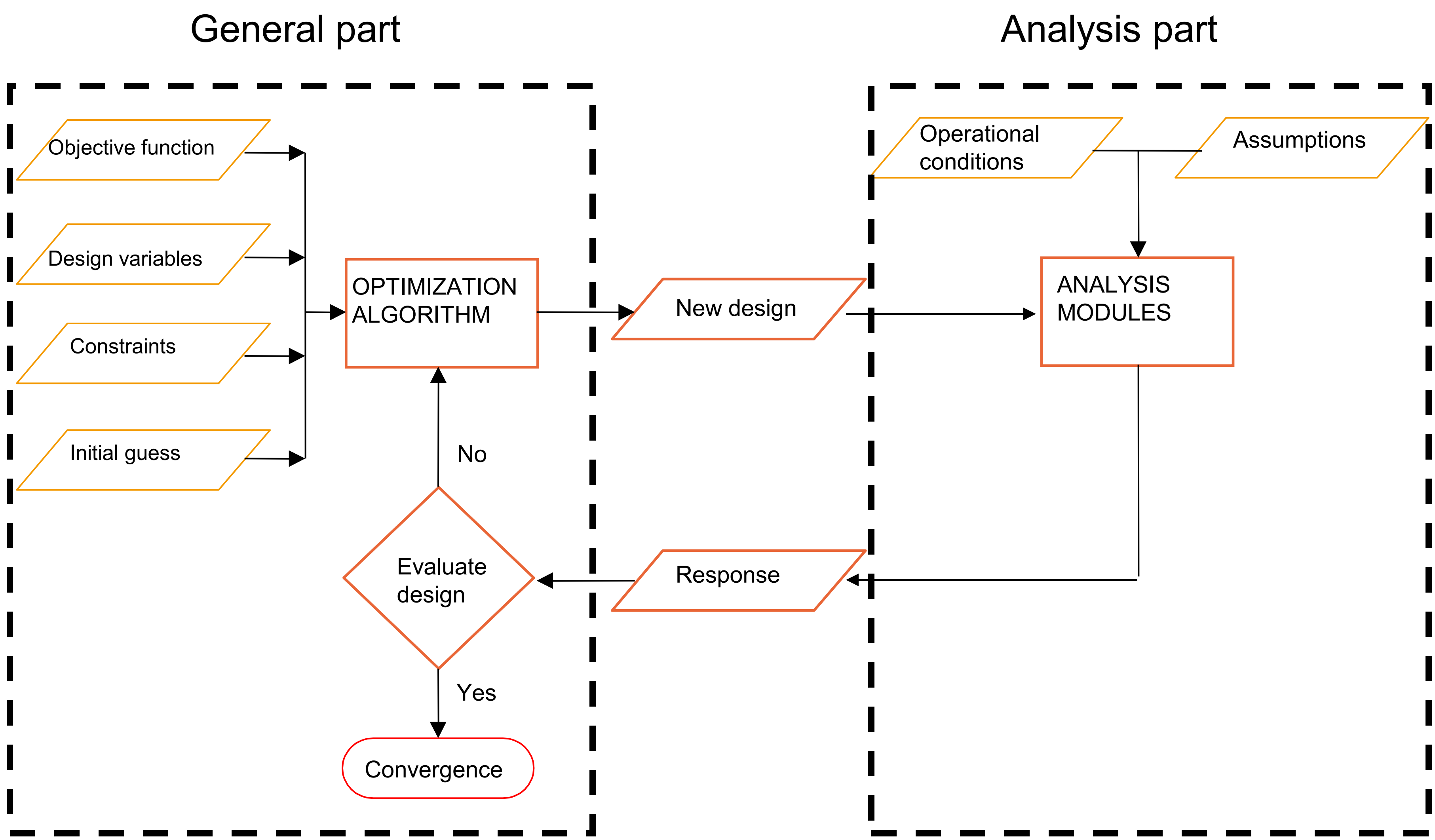


Rotor design
HAWTOPT: Possibilities

- The **analysis part** can contain:
  - Aerodynamic models (e.g. BEM)
  - Aeroelastic calculations (e.g. HAWC2)
  - Aeroelastic stability calculations (e.g. HAWCSTAB2)
  - Noise calculations (e.g. BPM-model)
  - Simple structural models (predicting mass, stiffness, tip deflection)

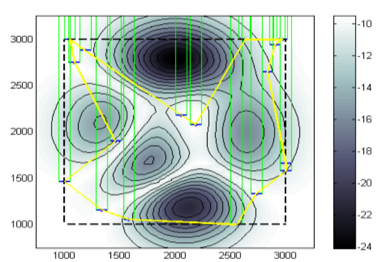
- The **general part** can contain**:**
  - **Object functions**:
    - CP, CT, power, thrust, Annual Energy Production (AEP), noise, fatigue loads etc.
  - **Design variables**:
    - Blade chord, twist, thickness distribution, tower height etc
  - **Constraints**:
    - Noise, CT, thrust, maximum chord, blade thickness, tip deflection, fatigue loads etc

Rotor design
HAWTOPT: Program structure

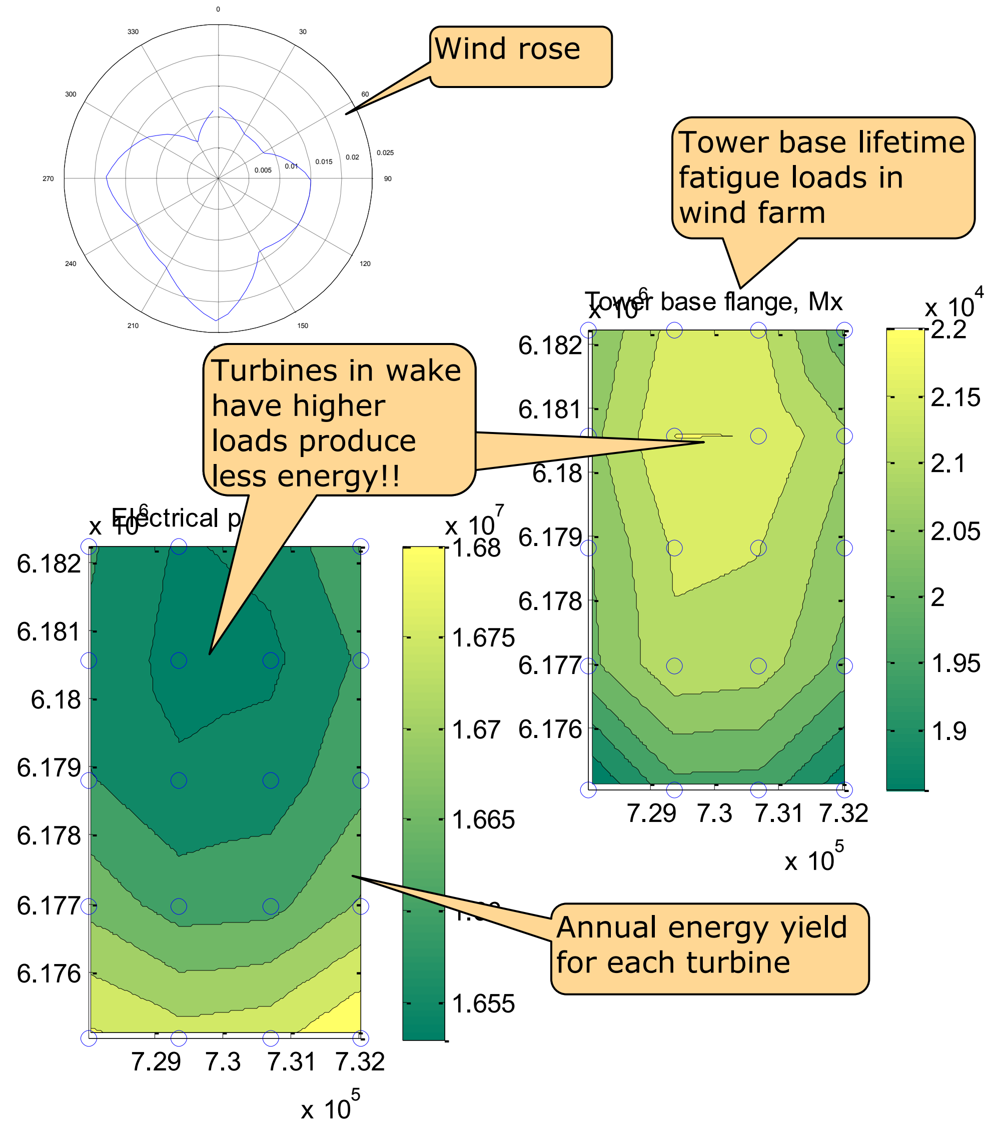


Topfarm wind farm optimization approach - loads and power

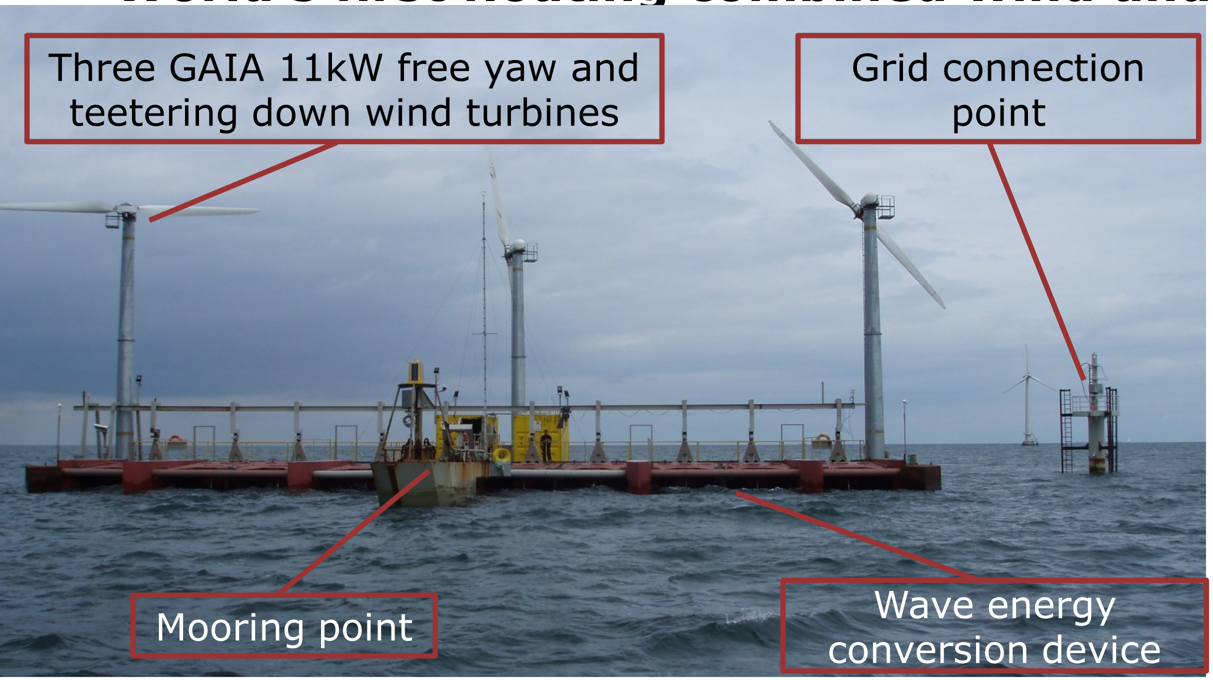
- Fast and robust optimization scheme for placing of wind turbines for optimum (lowest) cost of energy
- Wake modeling using DWM (Dynamic Wake Meandering)
- Quick lookup and summation for lifetime fatigue loads in a database based on HAWC2 aeroelastic simulations
- Cost function including: Annual energy production and costs of: Turbines, Grid, Foundation and O&M



Example: A 20 WT wind farm

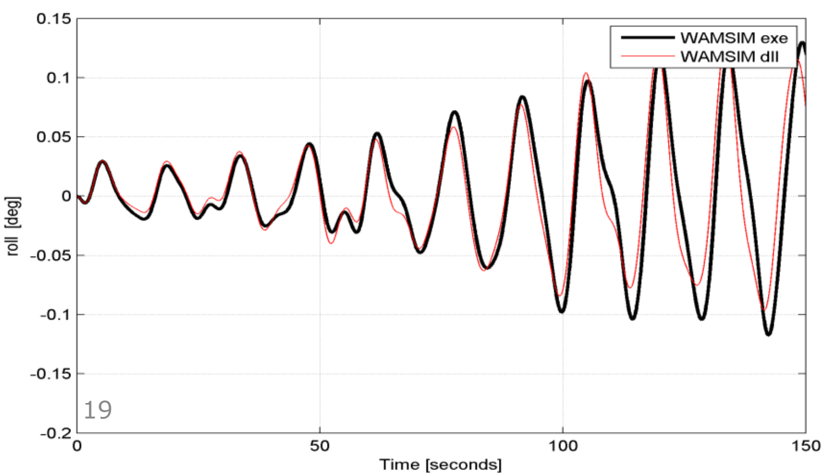


Combined wind and wave energy – Poseidon
World's first floating combined wind and wave energy plant

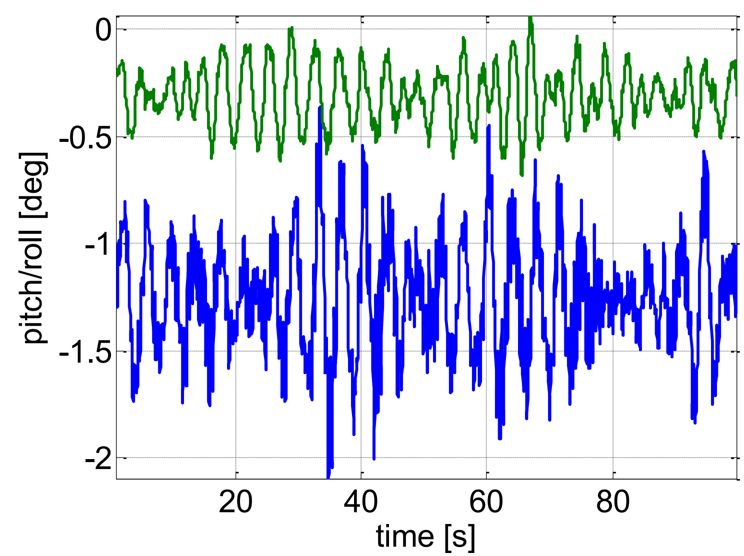


- Primarily a wave energy platform
- Large dimensions makes it stable and suitable for wind turbines
- Has been operating for 4 months
- Comprehensive measurement campaign
- Modeling and simulation work is ongoing

Code to code validation of new modeling tool

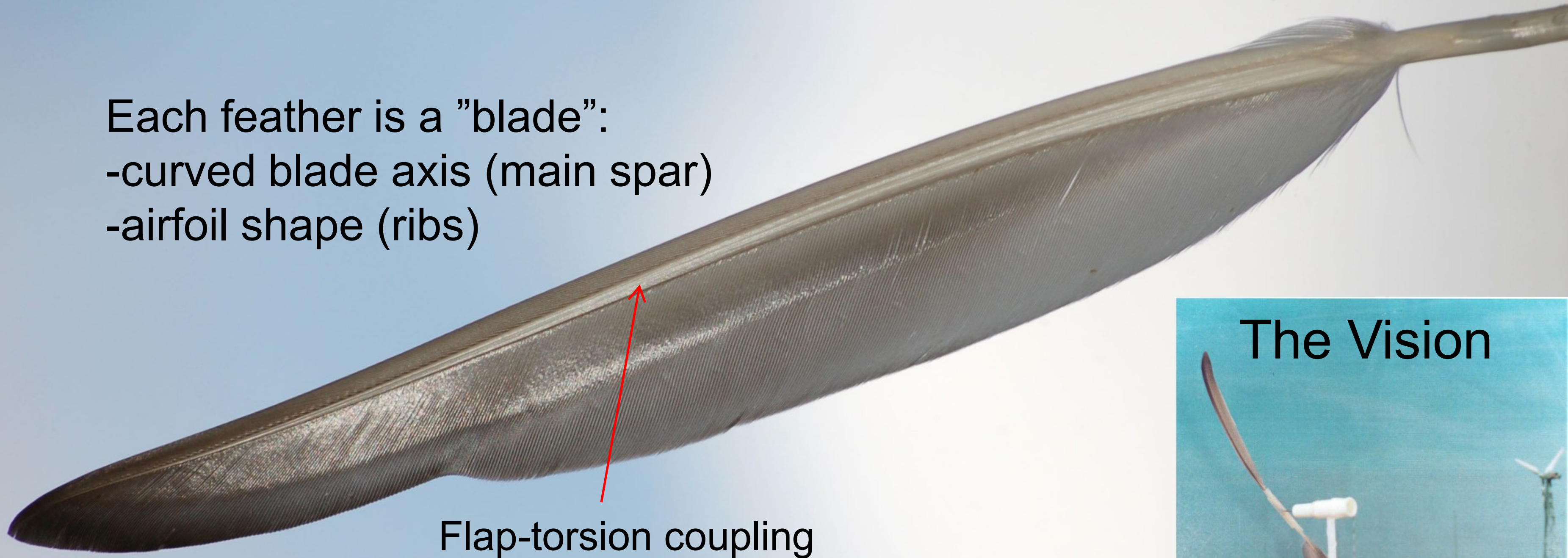


platform motion; H_0 = 0.48 m and Ws = 9.5 m/s



An example of Integrated Design

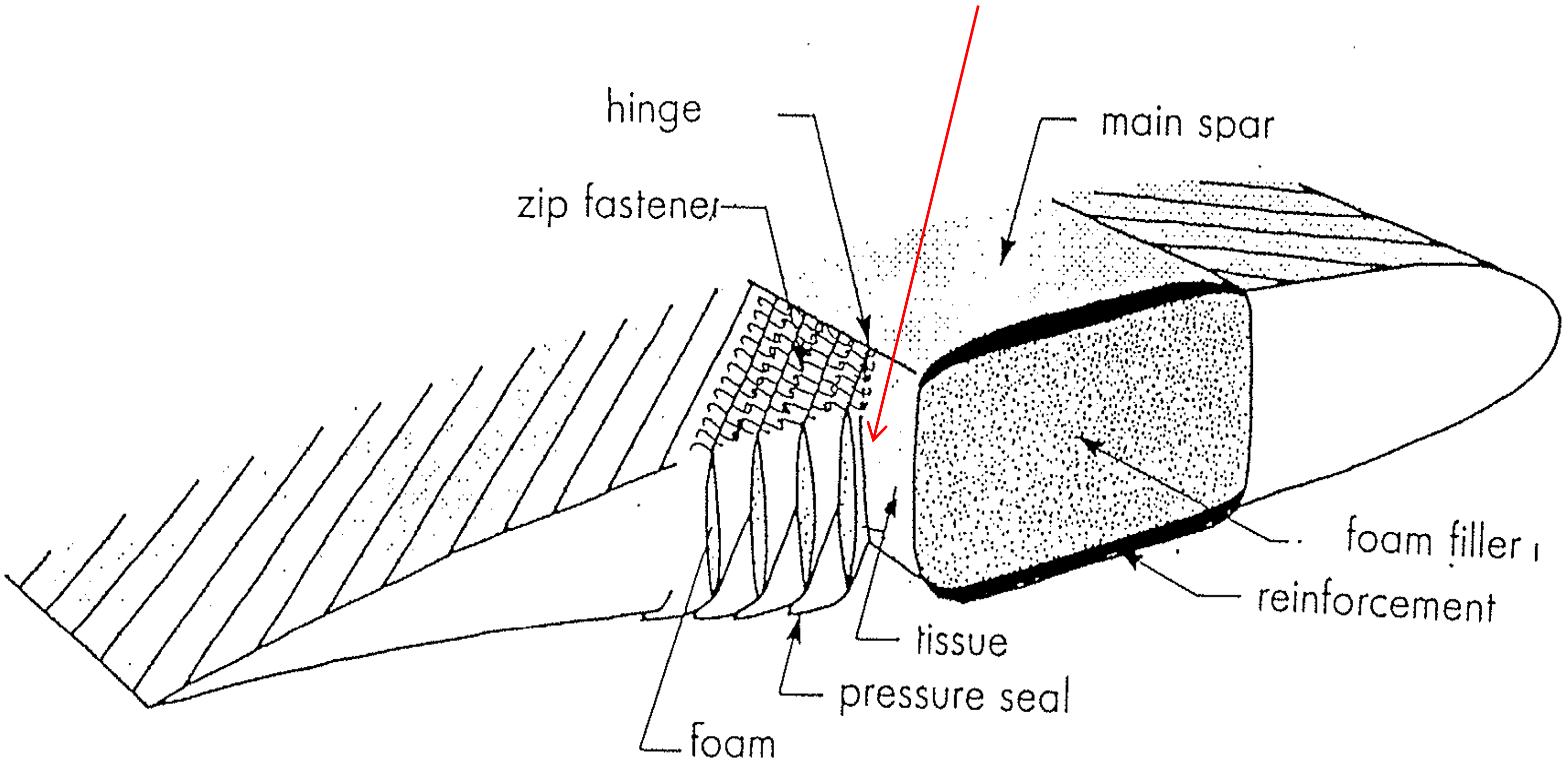
Each feather is a "blade":
-curved blade axis (main spar)
-airfoil shape (ribs)



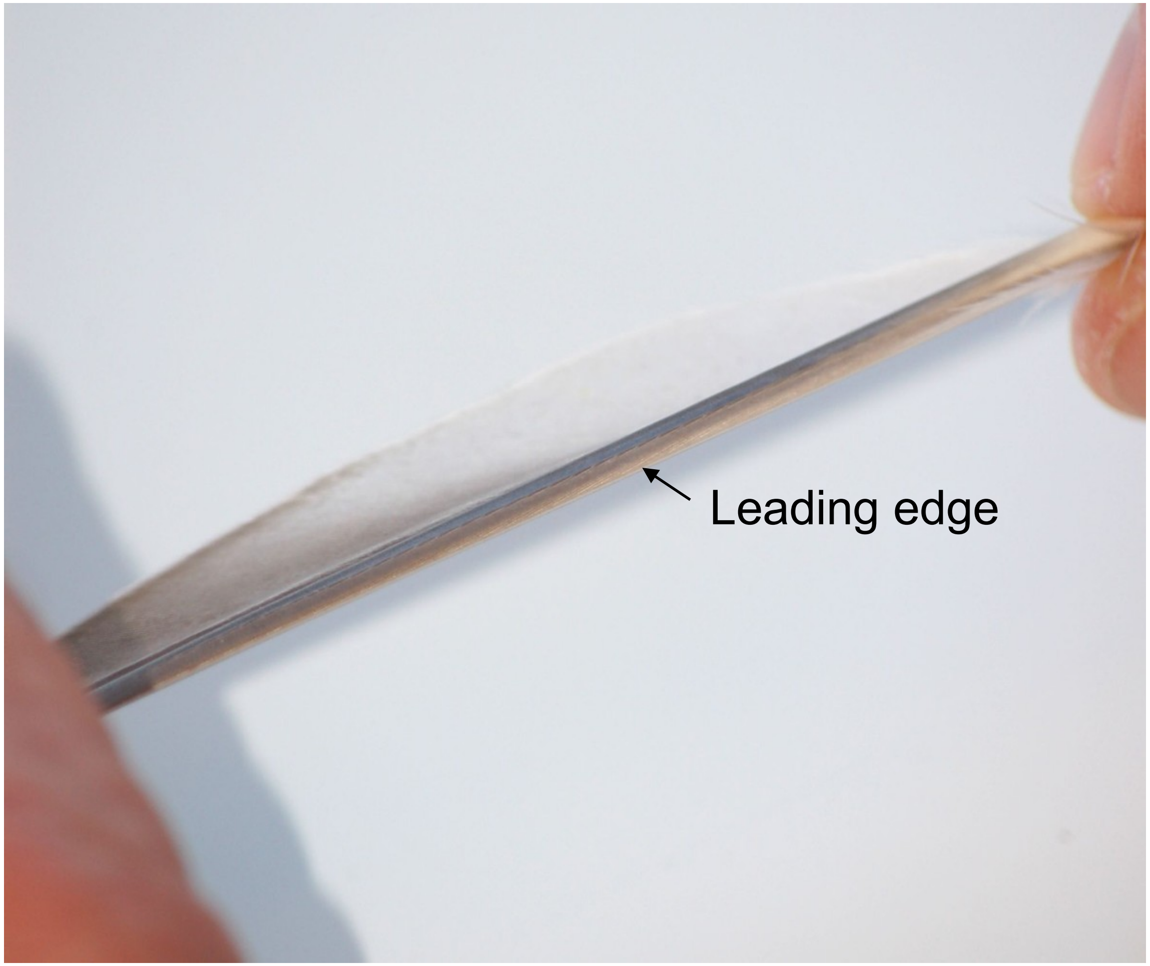
Flap-torsion coupling
due to sweep

Cross section of feather

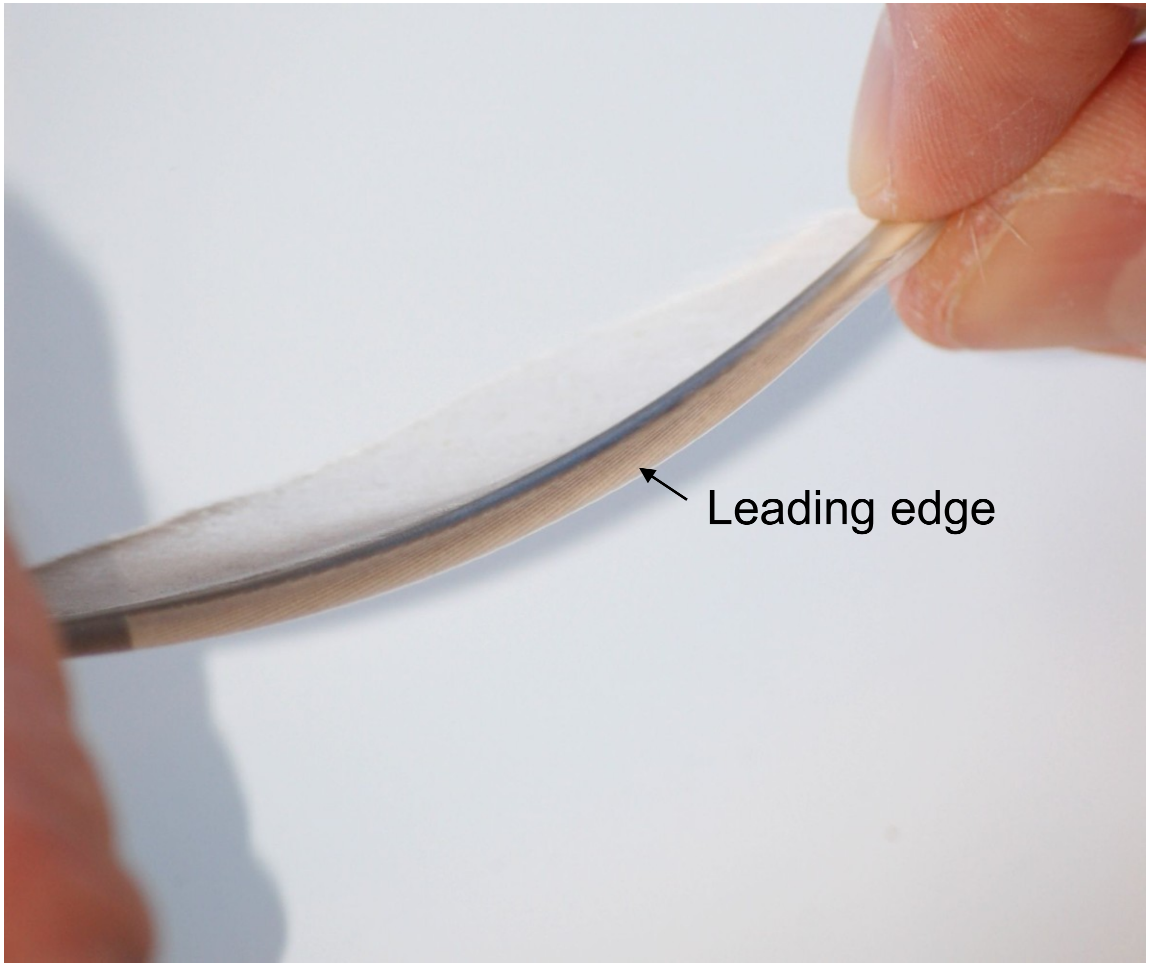
Flap-camber coupling due to rotation of ribs from shear web deformation



Flap-camber coupling



Flap-camber coupling



Integrated Design: Wing tip is a propeller