Department of Mechanical and Electrical Engineering

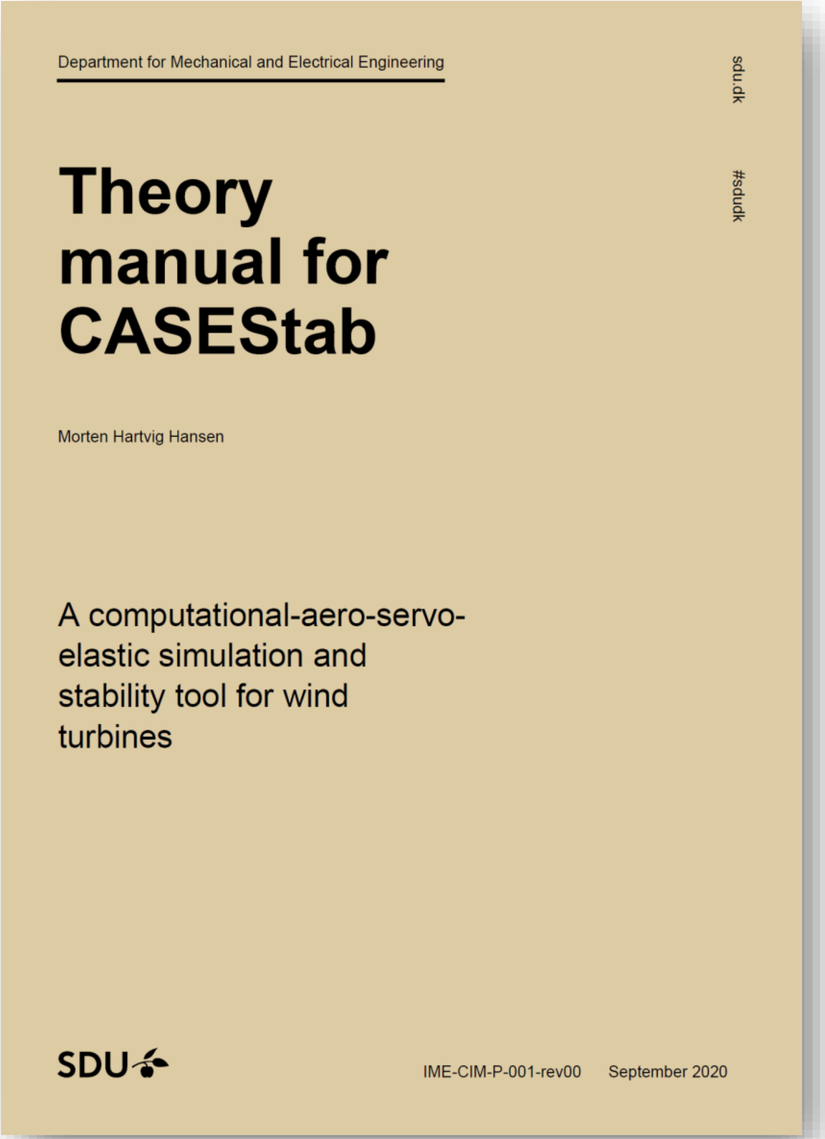
CASEStab

- status
- input formats
- validation

To be released under GNU AGPLv3 license
Repo: github.com/profhansen/CASEToolBox

CASEStab

- Computational-Aero-Servo-Elastic tool for wind turbine design and analysis
- Articulated substructures in a floating frame formulation
- Different substructure types
  - Co-rotational beam elements with non-constant, full 6x6 stiffness matrix
    - Parameters may be constant or vary linearly, quadratically, etc. over the element
  - Rigid bodies with possible flexible connection points (e.g. pitch bearing on a hub)
  - Linear (Craig-Bampton) and nonlinear (Lucas' PhD project) super-elements
- Aerodynamic wake and airfoil models inspired by HAWC2
  - More robust BEM iterations than HAWCStab2
  - Localized dynamic inflow with yaw/upflow corrections
  - Beddoes-Leishman dynamic stall
- Wind field from Mann turbulence boxes
- Different functionalities
  - Steady state computations power, loads, and deflections (stationary and periodic)
  - Structural blade and turbine modal analysis
  - Open- and closed-loop stability and frequency-domain load analyses
  - Nonlinear load simulations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Theory manual for CASEStab

Morten Hartvig Hansen

A computational-aero-servo-elastic simulation and stability tool for wind turbines

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IME-CIM-P-001-rev00 September 2020

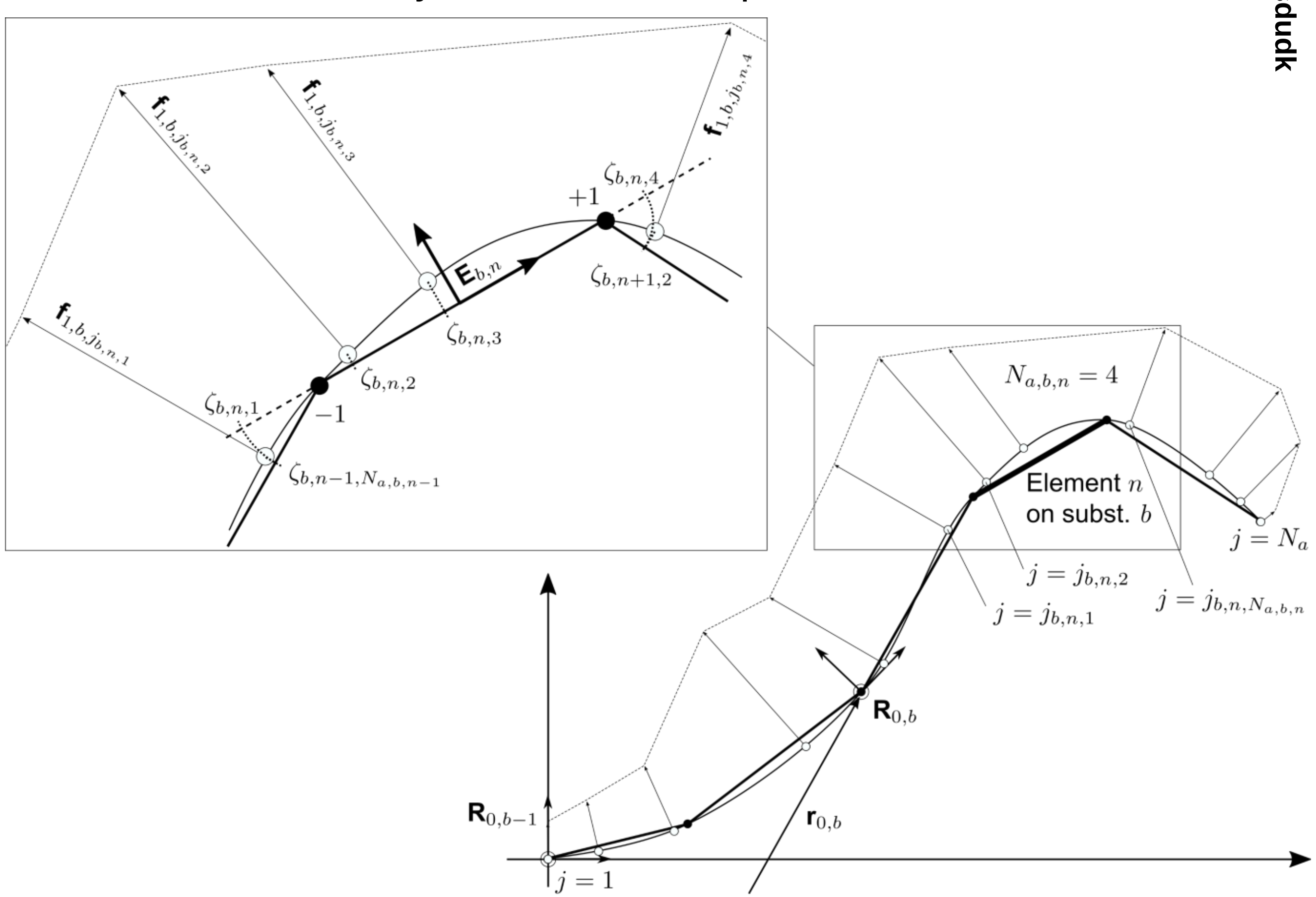
CASEStab status

- → Co-rotational beam element formulation
  - → Internal inertia and elastic forces are implemented
    - → Deflection due to centrifugal forces
    - → Structural blade mode shapes including centrifugal stiffness
  - → External forces are almost implemented
    - → Linear interpolation of sectional forces
    - → Interpolation across substructures, e.g. partial-pitched blades

- → Stationary steady-state computation
  - → Power and thrust curves
  - → Mean blade deflection, loads, and aerodynamic states

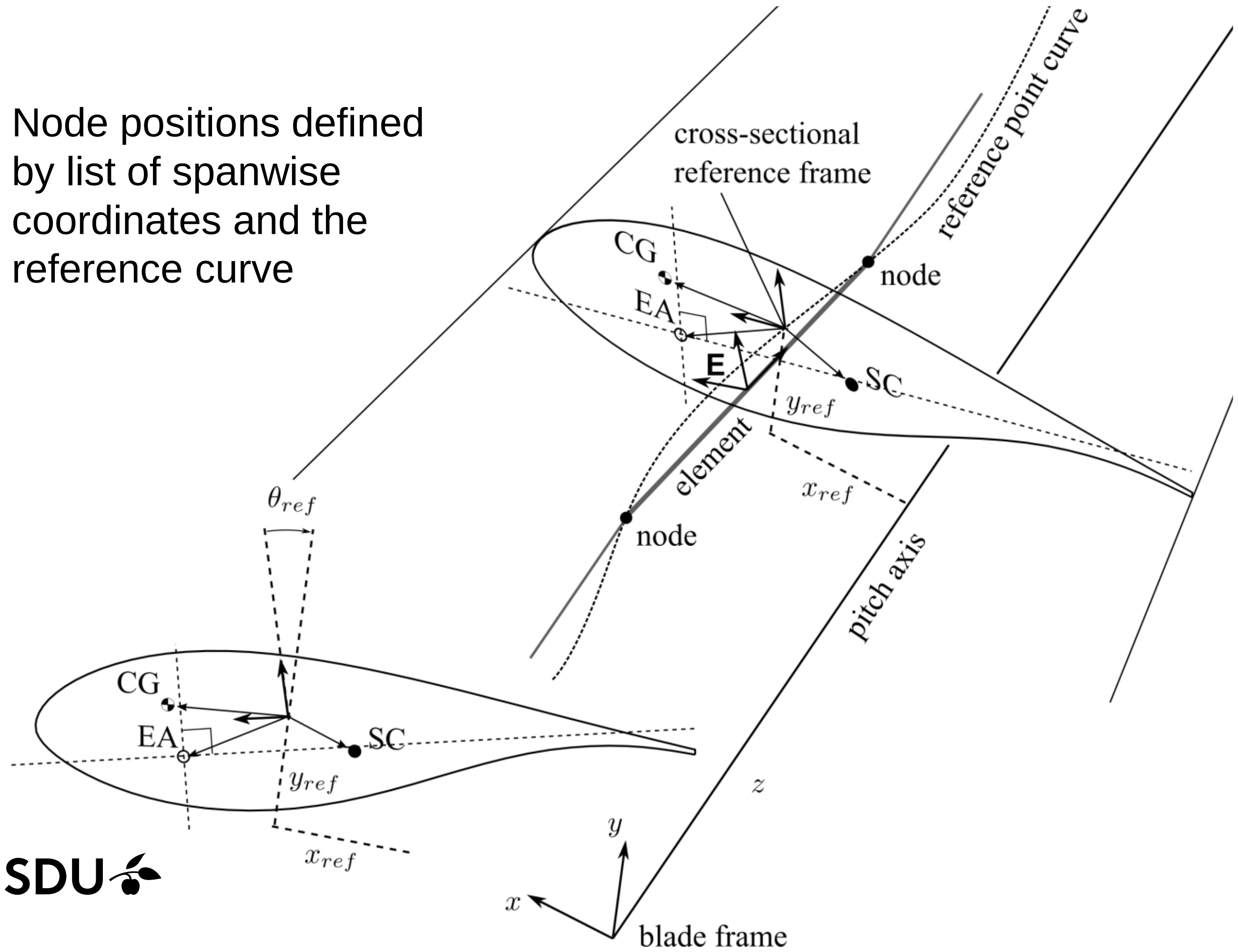
- → Structural blade modes for undeflected and deflected blades (pending issue on the latter)

Illustration from theory manual on interpolation of external forces



Structural input for co-rotational beam elements

Node positions defined by list of spanwise coordinates and the reference curve



Reference system:		
1	z [m]	Distance to section from base of substructure (blade root flange) along the third (pitch) axis of the substructure (blade) frame.
2	x_{ref} [m]	Primary (edge) axis distance from third substructure (pitch) axis to the origin (the reference point) of the cross-sectional reference frame.
3	y_{ref} [m]	Secondary (flap) axis distance from third substructure (pitch) axis to the origin (the reference point) of the cross-sectional reference frame.
4	θ_{ref} [deg]	Angle of inplane rotation of the cross-sectional two-dimensional reference frame. Each element coordinate system is rotated the element-average of this angle from an initial orientation where its secondary (flap) axis has a zero primary (edge) axis component in the substructure (blade) frame.
Mass properties:		
5	m [kg/m]	Mass per unit-length of the substructure.
6	x_{cg} [m]	Distance on primary axis of the reference frame from reference point to mass center (CG).
7	y_{cg} [m]	Distance on secondary axis of the reference frame from reference point to mass center (CG).
8	r_x [m]	Radius gyration for rotation about the primary inertia axis with CG as origin.
9	r_y [m]	Radius gyration for rotation about the secondary inertia axis with CG as origin.
10	θ_{rx} [deg]	Angular offset of the primary inertia axis from the primary axis of the reference frame.
Stiffness properties (isotropic section = 13 columns or full 6x6 compliance matrix = 21 columns)		
Isotropic section:		
11	x_{ea} [m]	Distance on primary axis of the reference frame from reference point to the centroid of bending (elastic axis).
12	y_{ea} [m]	Distance on secondary axis of the reference frame from reference point to the centroid of bending (elastic axis).
13	x_{sc} [m]	Distance on primary axis of the reference frame from reference point to the shear center.
14	y_{sc} [m]	Distance on secondary axis of the reference frame from reference point to the shear center.
15	θ_{bend} [deg]	Angular offset of the primary bending axis from the primary axis of the reference frame (structural twist).
16	E [Pa]	Average elastic Young's modulus of the cross-section.
17	G [Pa]	Average shear modulus of the cross-section.
18	A [m^2]	Area of cross-section.
19	I_x [m^4]	Moment of inertia for bending about the primary bending axis.
20	I_y [m^4]	Moment of inertia for bending about the secondary bending axis.
21	K [m^4]	Moment of inertia for torsion.
22	k_x [-]	Shear correction factor in the direction of the primary reference axis.
23	k_y [-]	Shear correction factor in the direction of the secondary reference axis.
Full 6x6 compliance matrix:		
11-31	**C** [SI]	Upper triangle 21 elements of the symmetric 6x6 compliance matrix row by row $[C_{11}, C_{12}, \ldots, C_{16}, C_{22}, \ldots, C_{66}]$ given in the reference frame.

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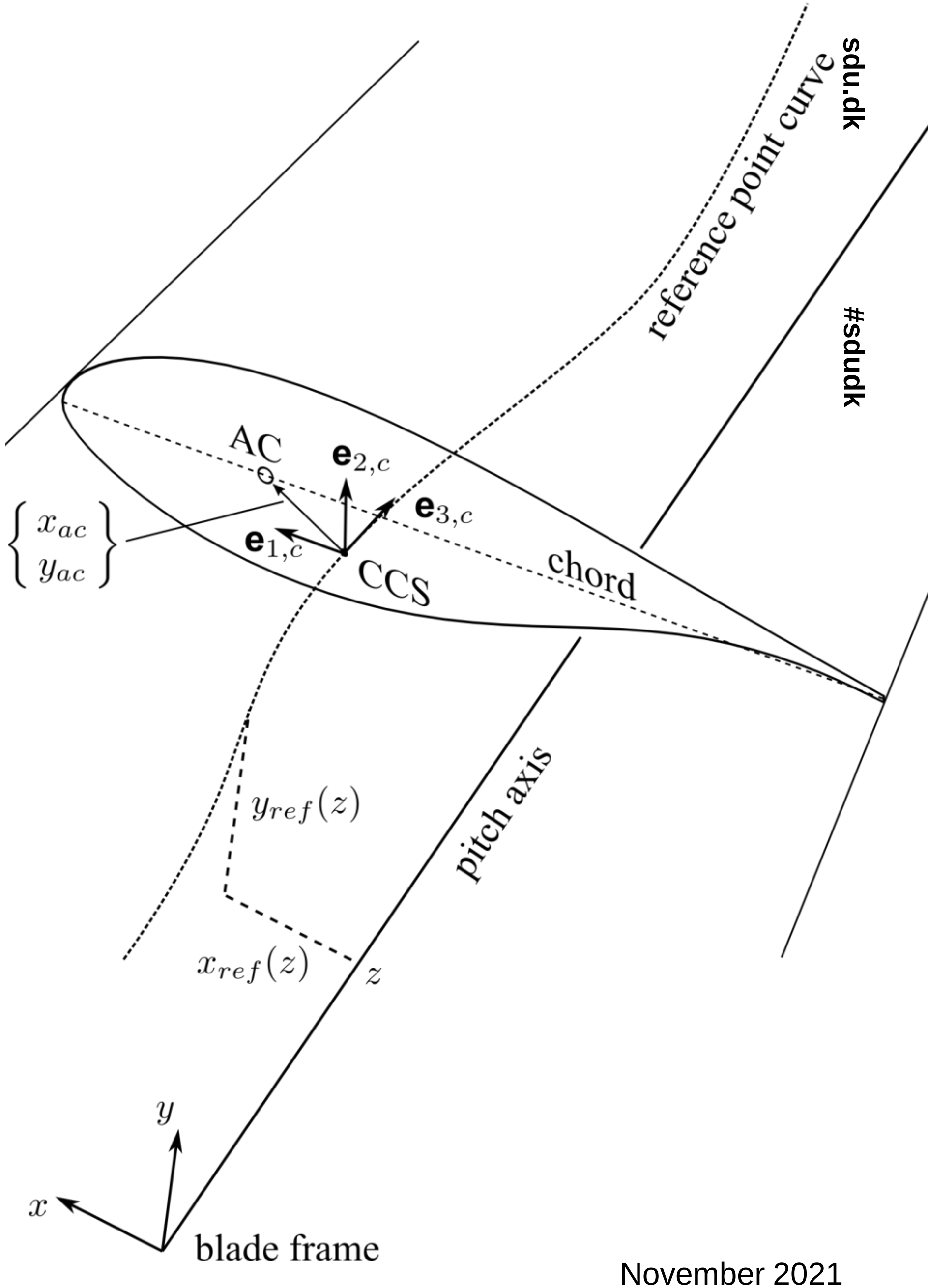
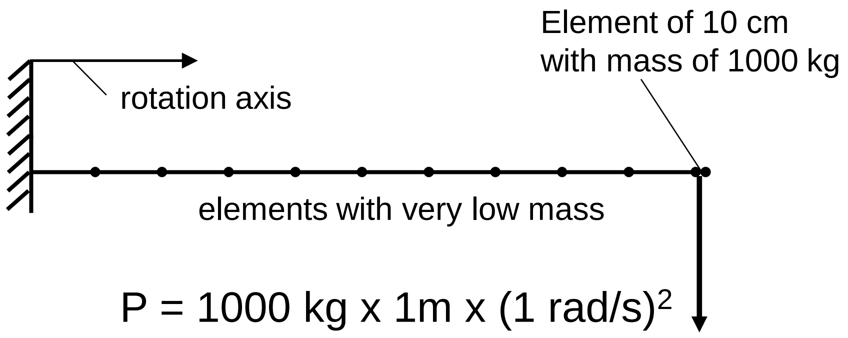
Aerodynamic input for blades

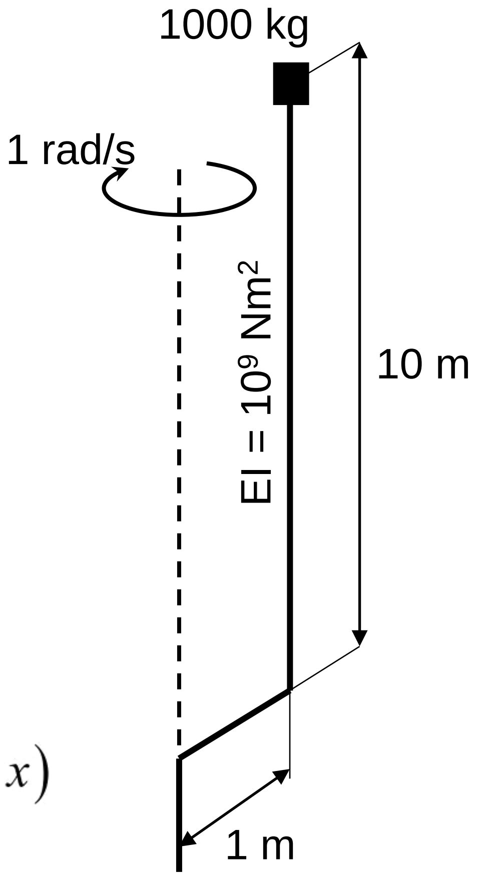
1	z [m]	Distance to section from base of substructure (blade root flange) along the third (pitch) axis of the substructure (blade) frame.
2	x_{ref} [m]	Primary (edge) axis distance from third substructure (pitch) axis to the reference point of the cross-sectional reference frame.
3	y_{ref} [m]	Secondary (flap) axis distance from third substructure (pitch) axis to the reference point of the cross-sectional reference frame.
4-6	ϕ_x, ϕ_y, ϕ_z [deg]	Pseudo vector of finite rotation of Chord Coordinate System (CCS) from the substructure (blade) frame. If $\phi_x = \phi_y = 0$, then the normal to the airfoil plane is defined by the tangent of the reference point curve and the inplane axes of the CCS are defined such that its secondary axis has zero primary axis component in the blade frame before rotating them about the tangent by ϕ_z.
7	c [m]	Chord length of airfoil or diameter of circle.
8	t_{rel} [%]	Relative thickness of airfoil (100% = circle).
9	x_{ac} [m]	Distance on primary axis of the reference frame from reference point to the aerodynamic center (AC).
10	y_{ac} [m]	Distance on secondary axis of the reference frame from reference point to the aerodynamic center (AC).
11	a_{ac} [-]	Non-dimensional chordwise position of the AC for visualization of the blade.
12	i_{pc} [-]	Number of the airfoil set in HAWC2 type polar data files.

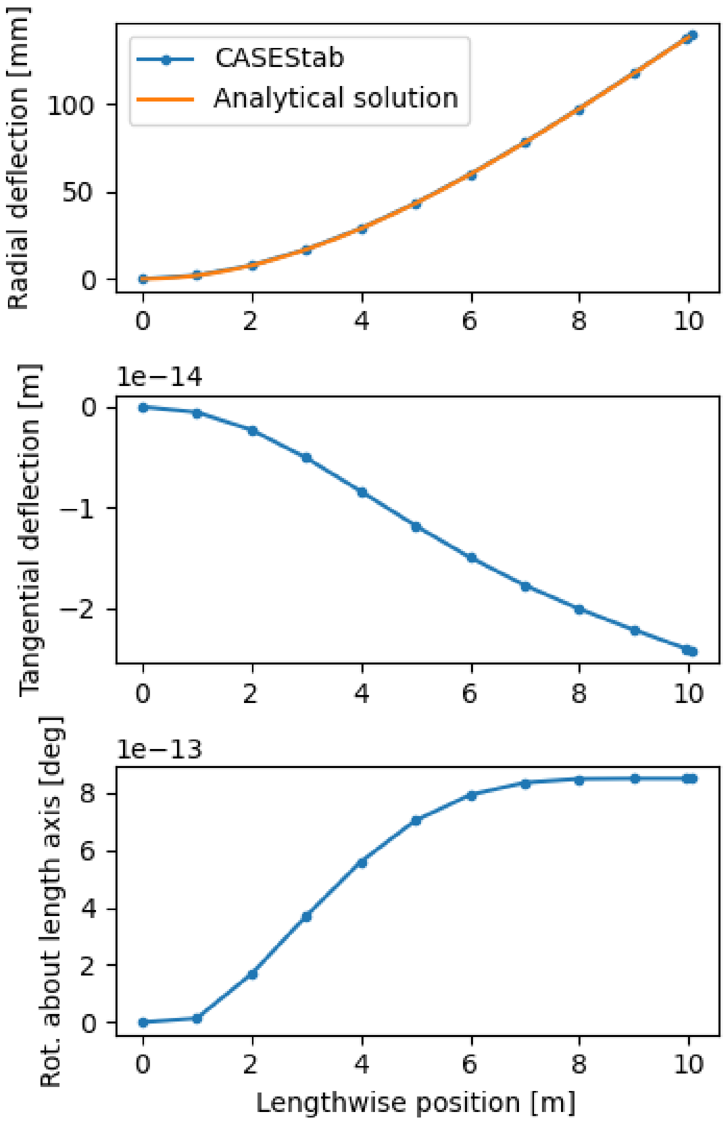


Validation of deflection under centrifugal force

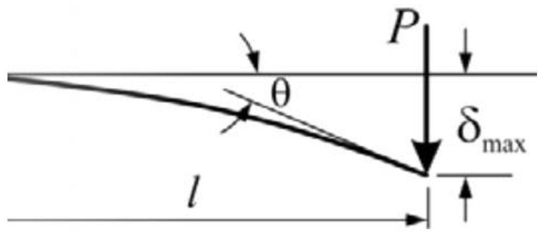
CASEStab model







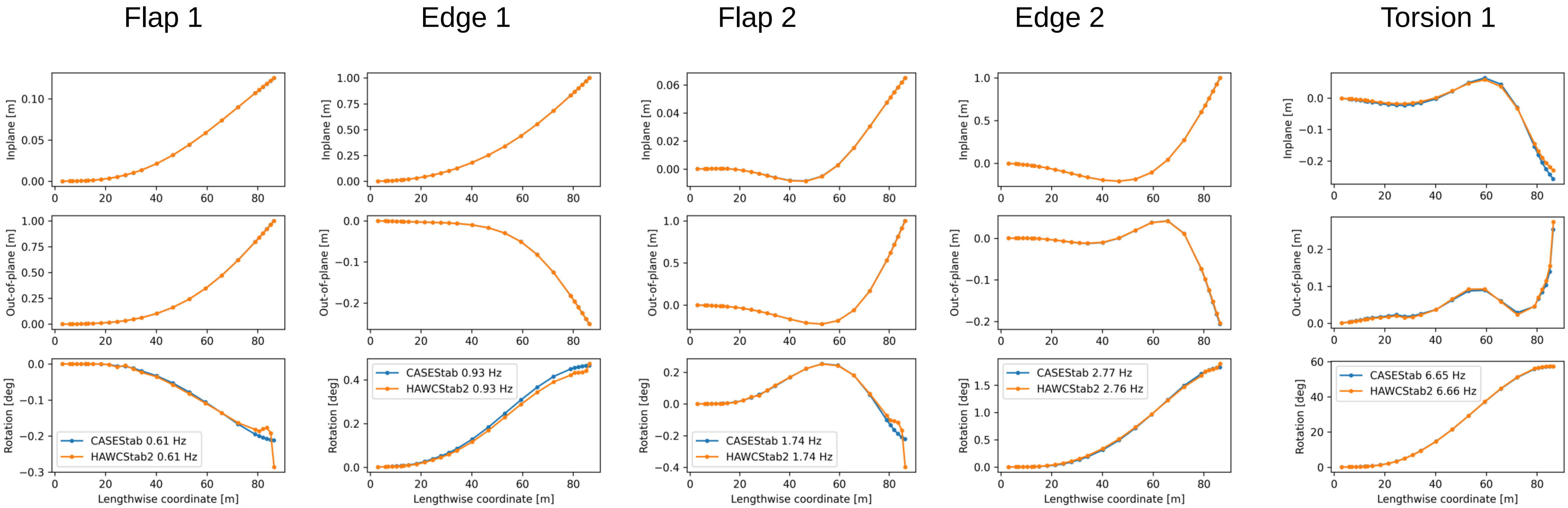
Analytical solution



$$y = \frac{Px^2}{6EI}(3l - x)$$

DTU10MW blade mode shapes at standstill

Element data directly imported from HAWC2’s export function “beam_output_file_name“



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DTU10MW blade mode shapes at standstill

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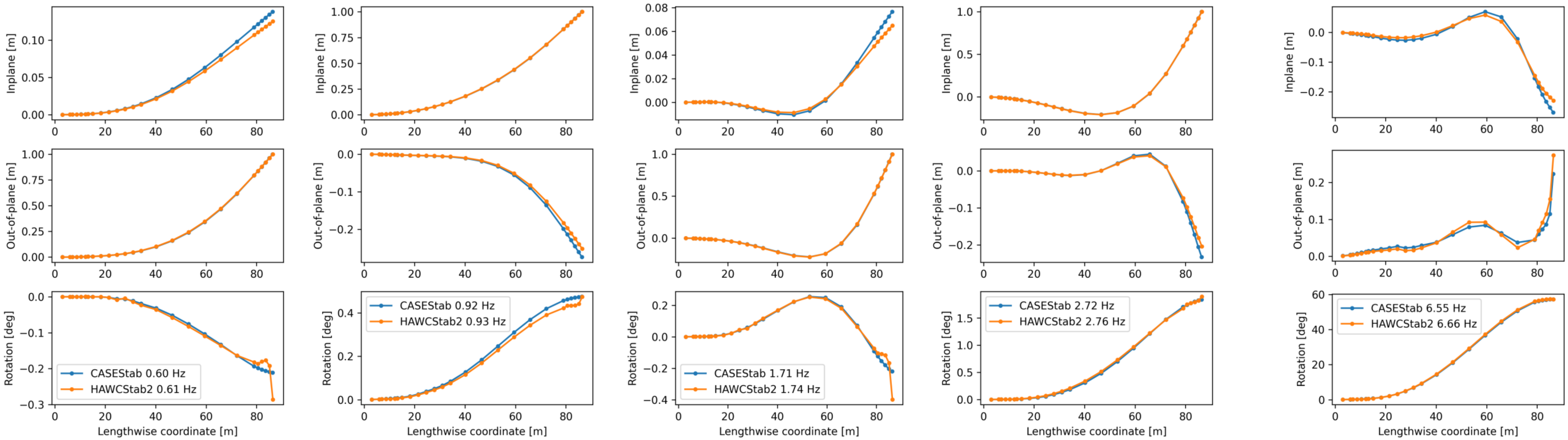
Isotropic element data interpolated and averaged (N=50) from converted isotropic HAWC2 ST-file

Flap 1 | Edge 1 | Flap 2 | Edge 2 | Torsion 1

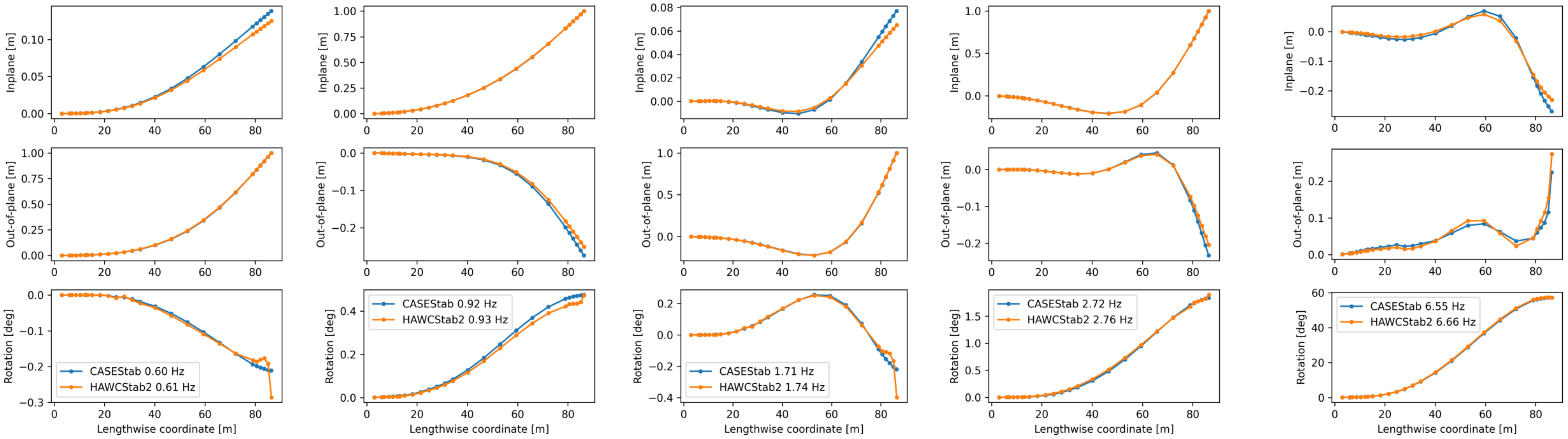


Difference in directions of vibration is due to the averaging of nonlinear functions of compliance matrix components.

DTU10MW blade mode shapes at standstill

6x6 element data interpolated and averaged (N=50) from converted isotropic HAWC2 ST-file

Flap 1 | Edge 1 | Flap 2 | Edge 2 | Torsion 1



Difference in directions of vibration is due to the averaging of nonlinear functions of compliance matrix components.

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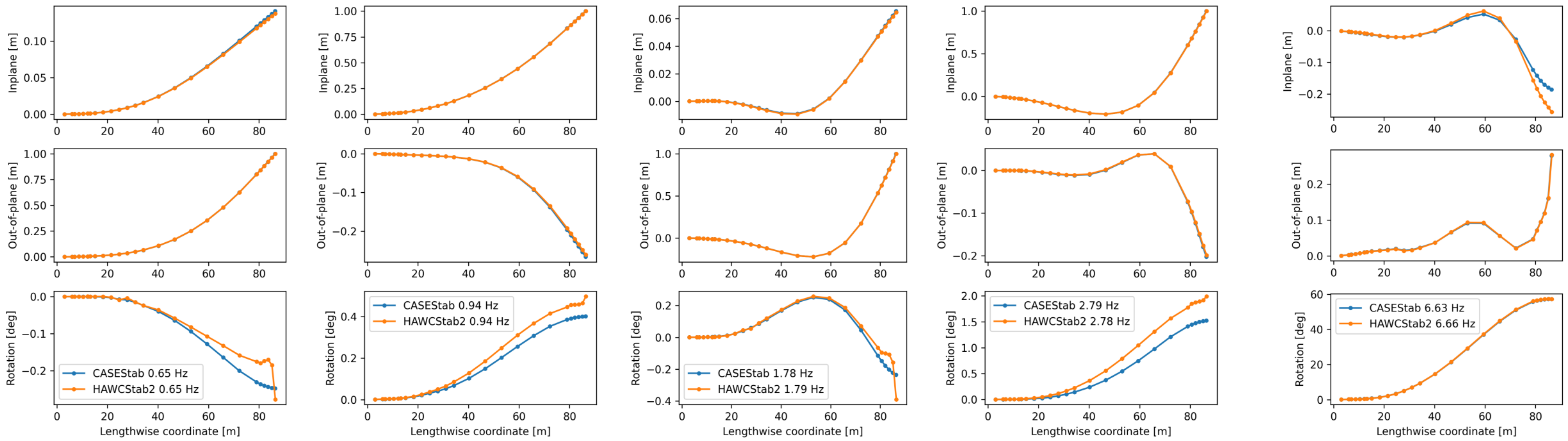
DTU10MW blade mode shapes at 10 rpm

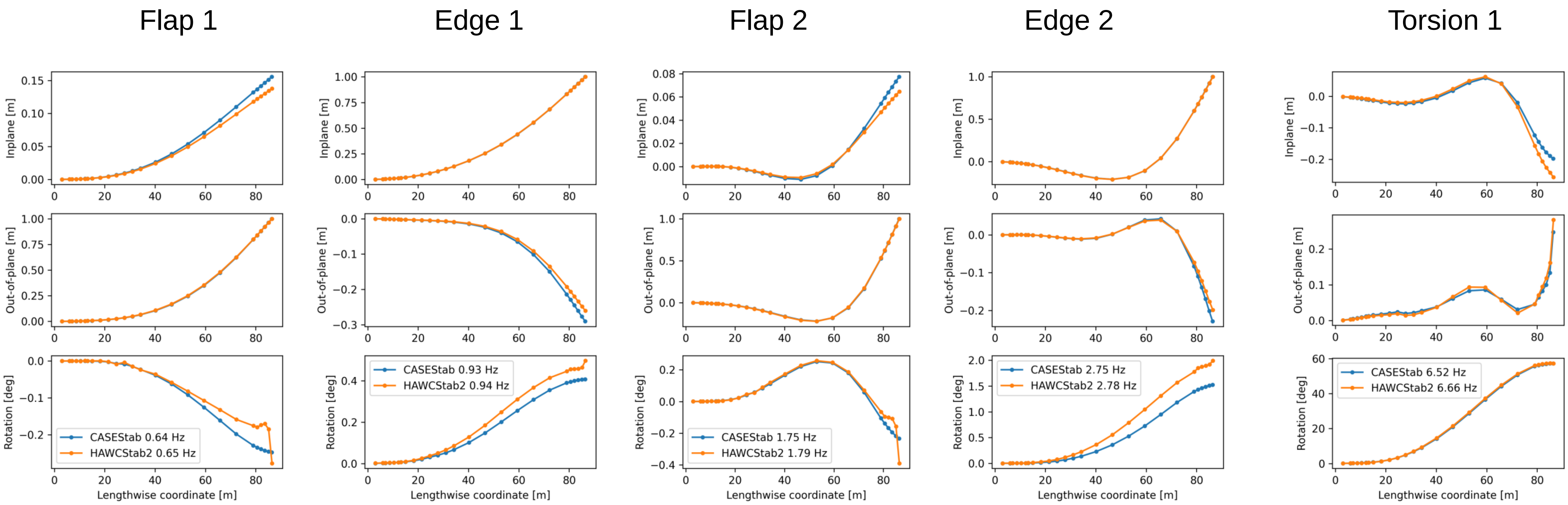
Element data directly imported from HAWC2's export function "beam_output_file_name"

Flap 1 | Edge 1 | Flap 2 | Edge 2 | Torsion 1



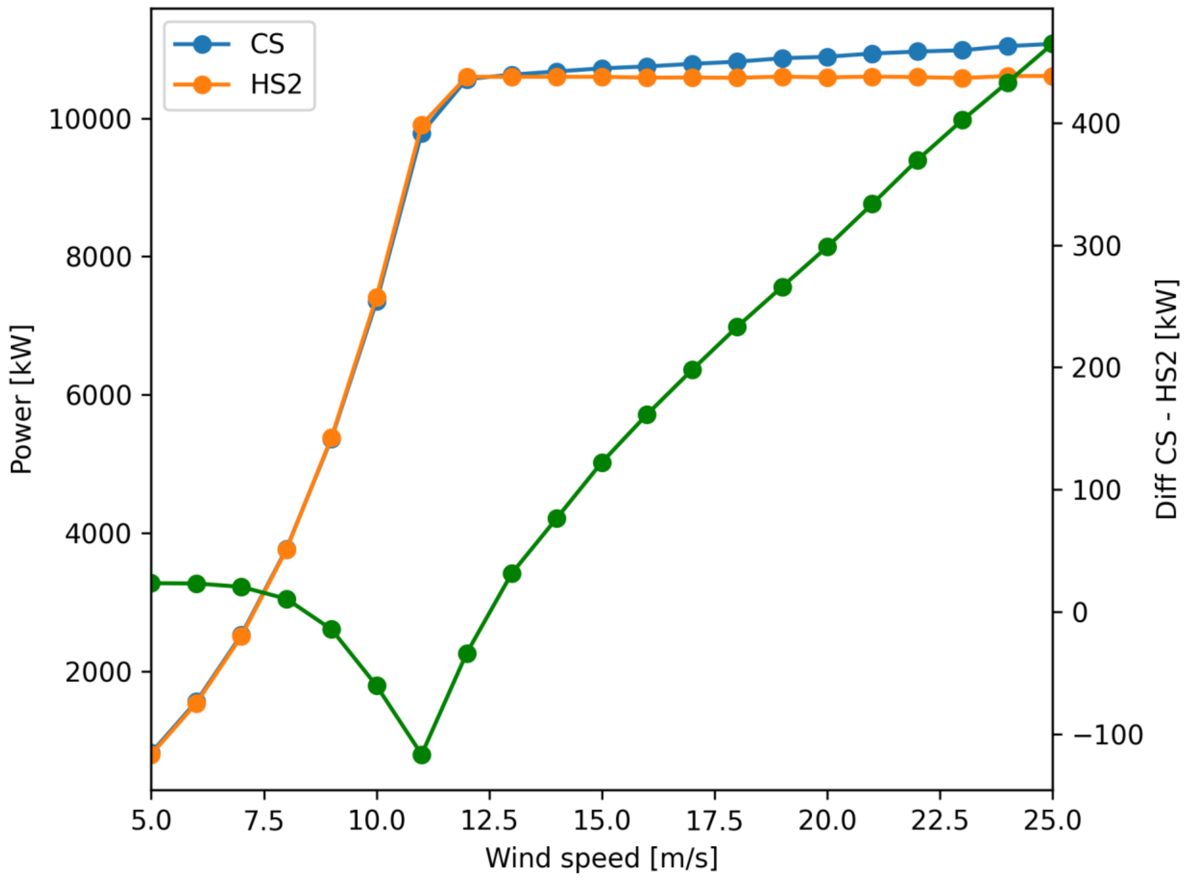
DTU10MW blade mode shapes at 10 rpm

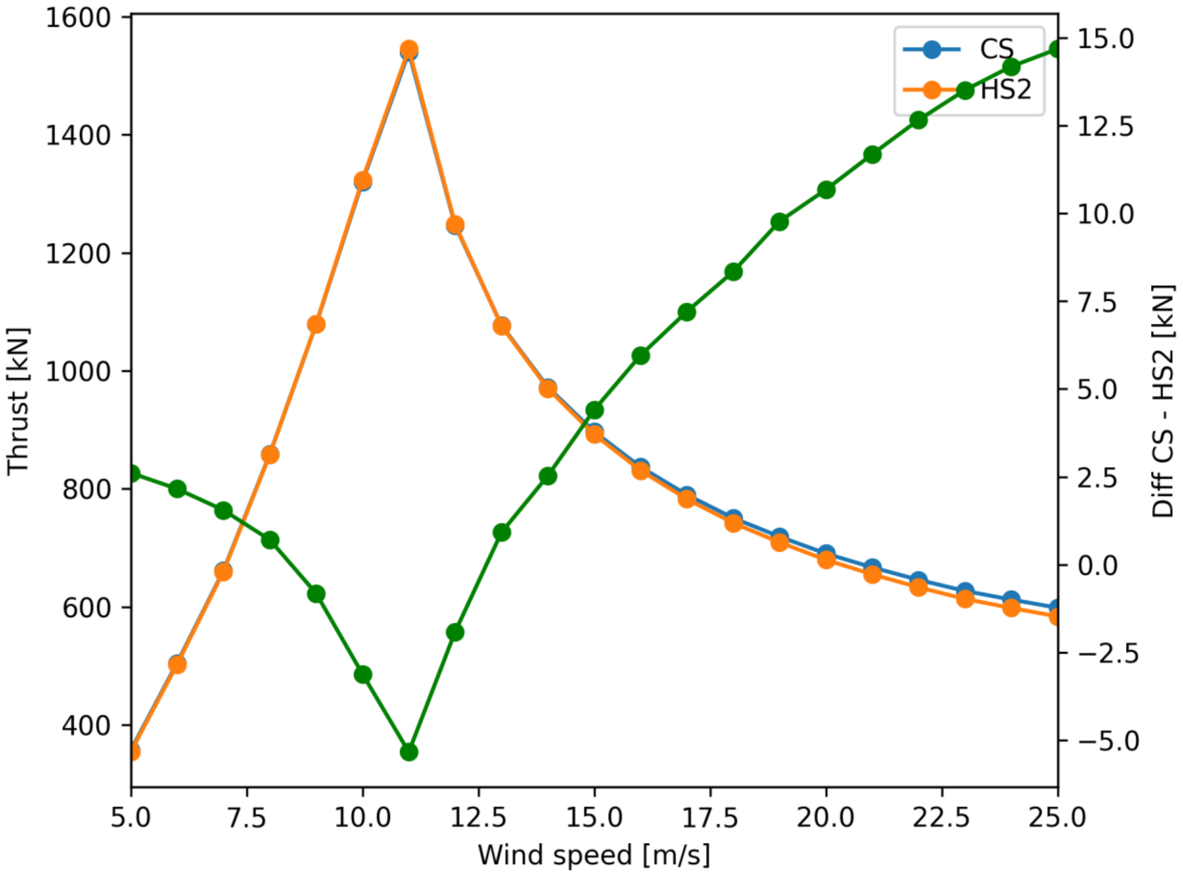
Isotropic element data interpolated and averaged (N=50) from converted isotropic HAWC2 ST-file



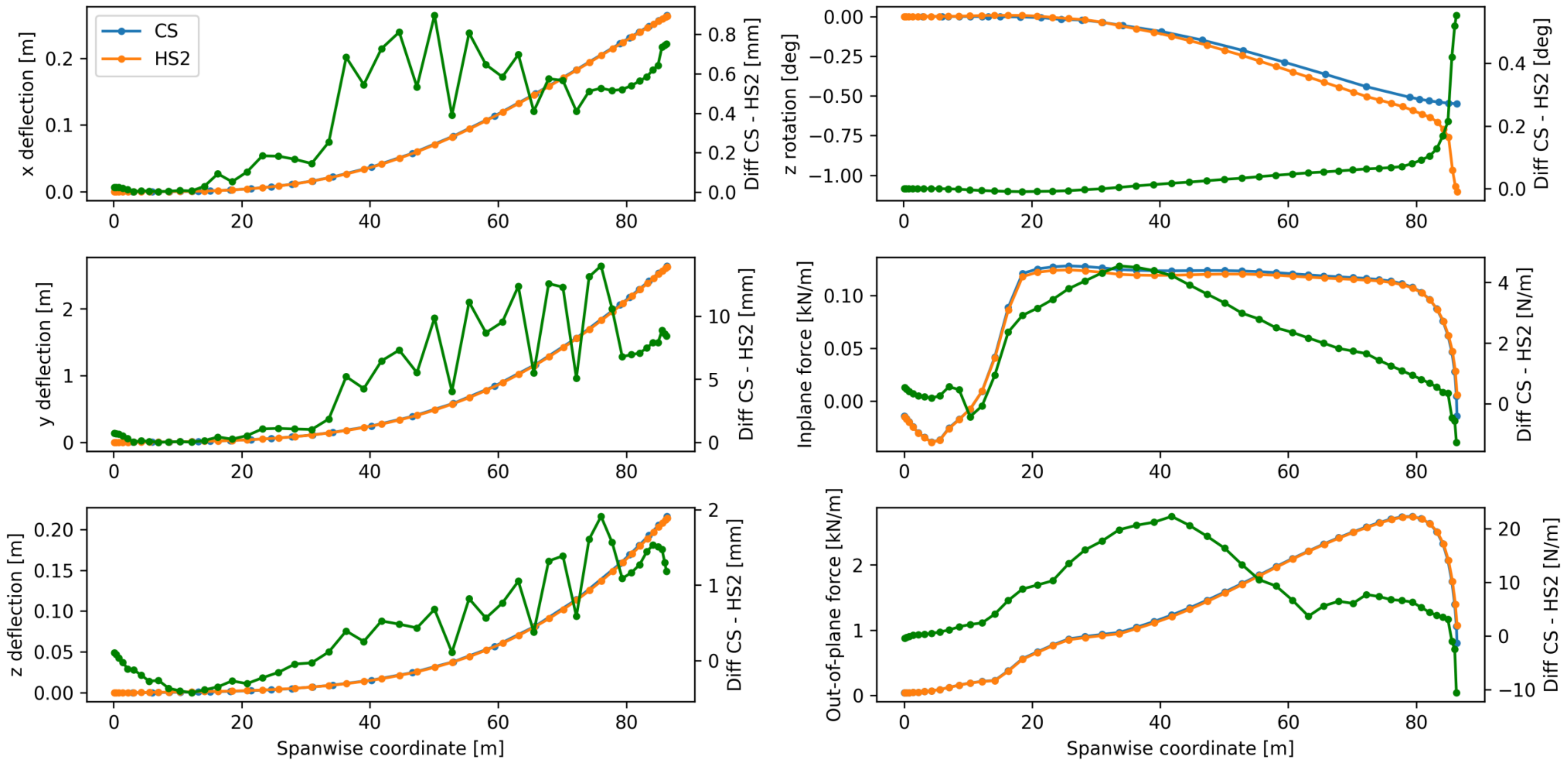
Difference in directions of vibration is due to the averaging of nonlinear functions of compliance matrix components.

DTU10MW Steady state computation

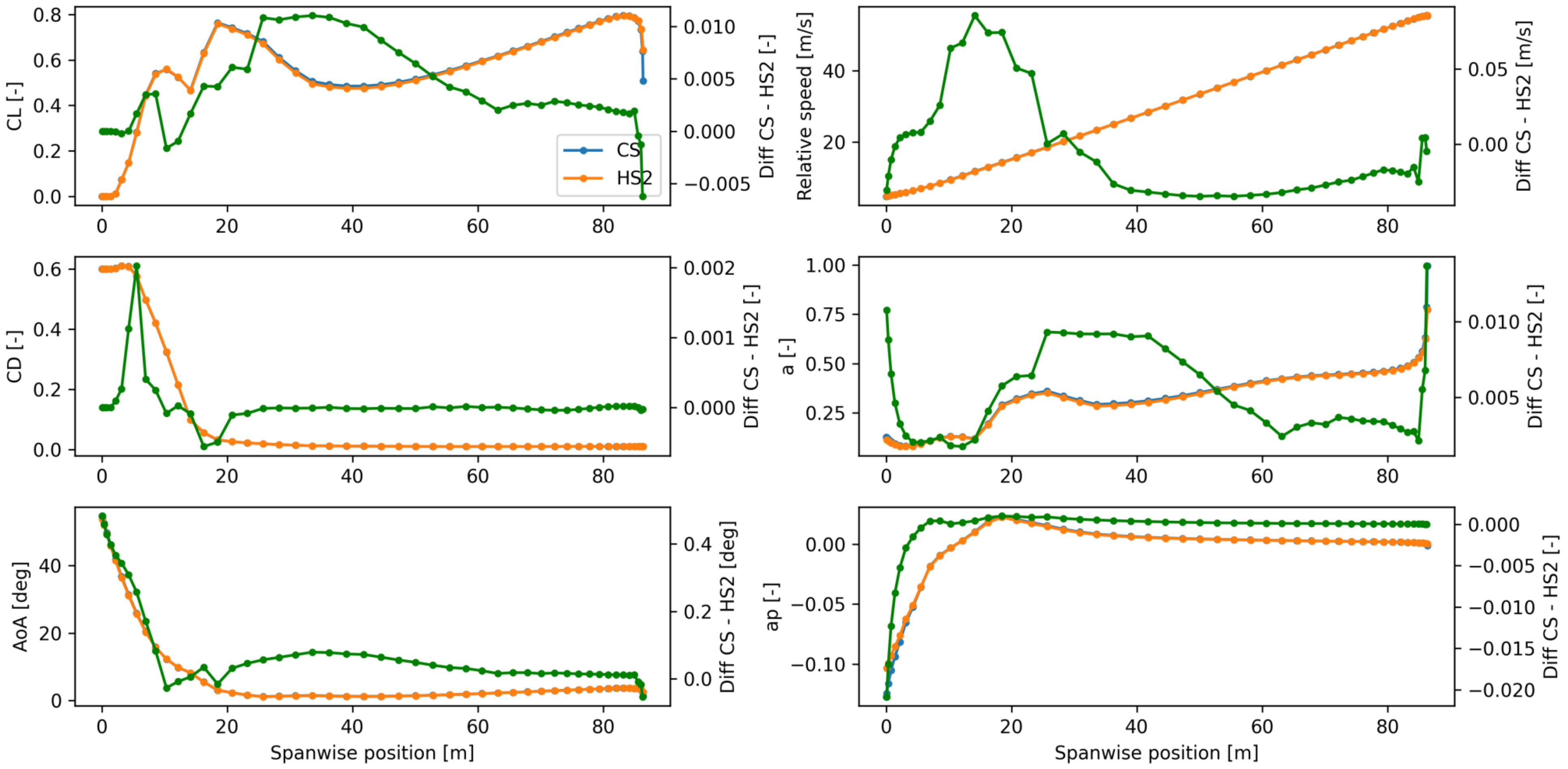




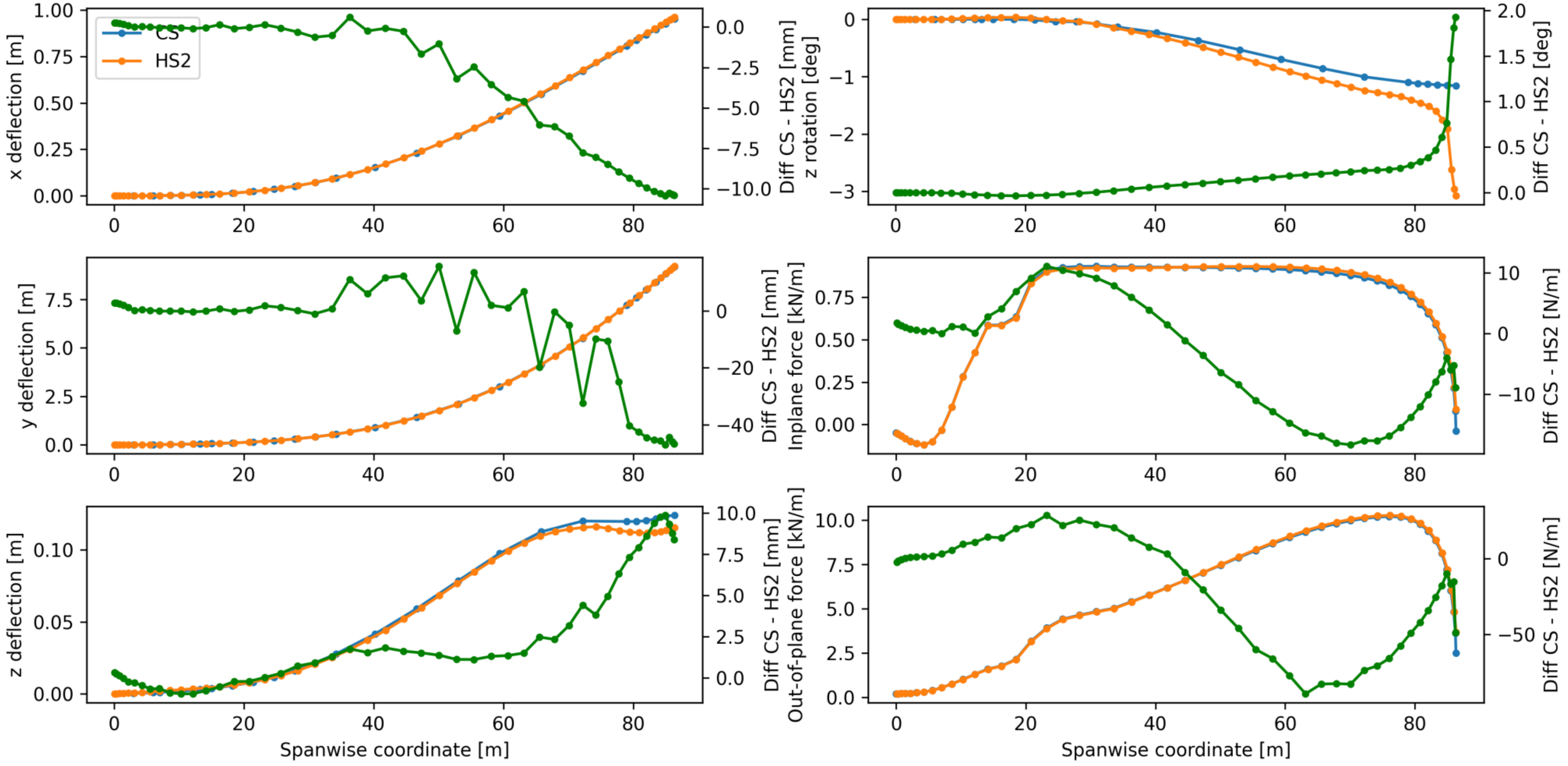
DTU10MW Steady deflection and forces 5 m/s



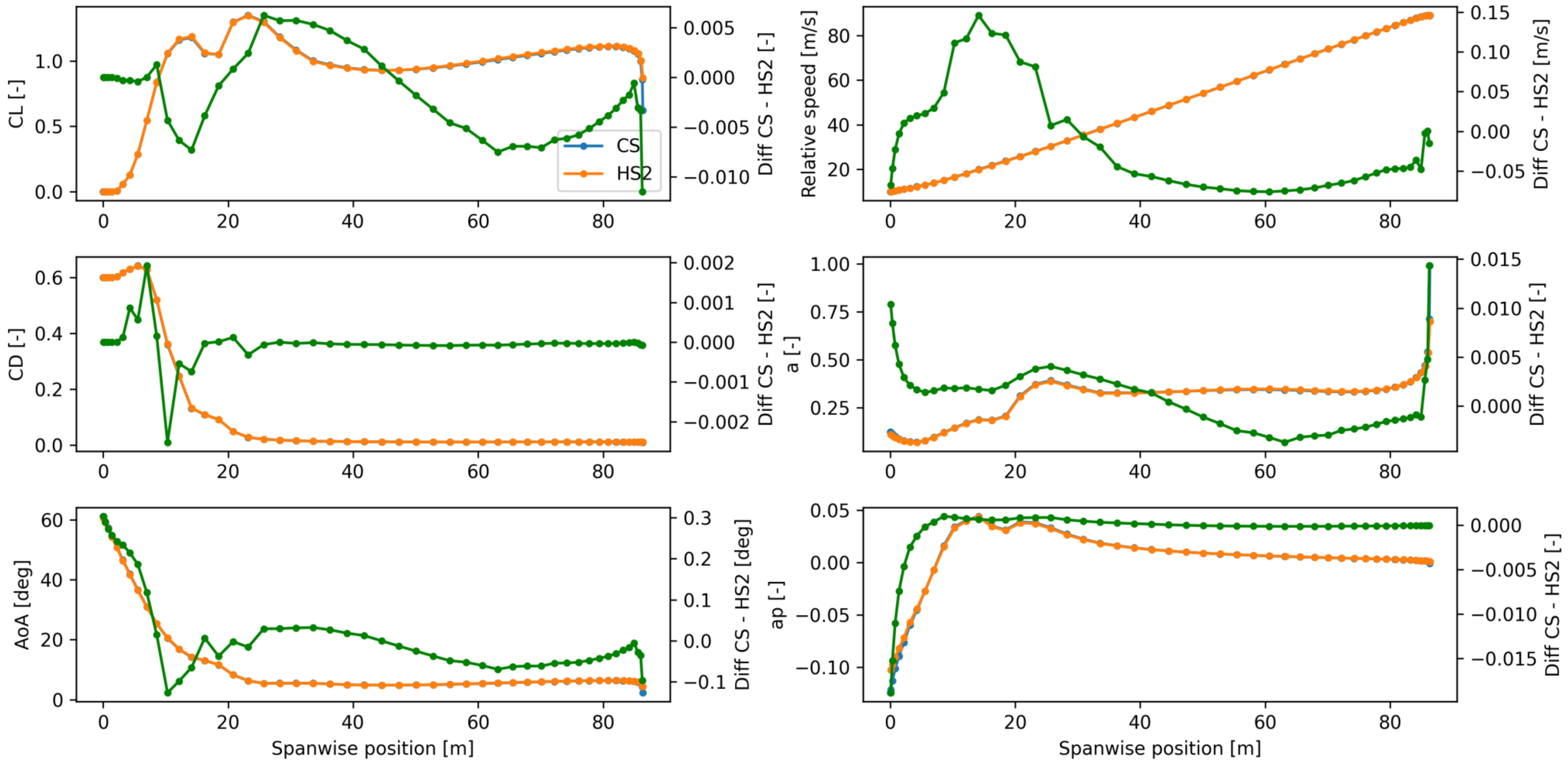
DTU10MW Steady velocity triangle 5 m/s



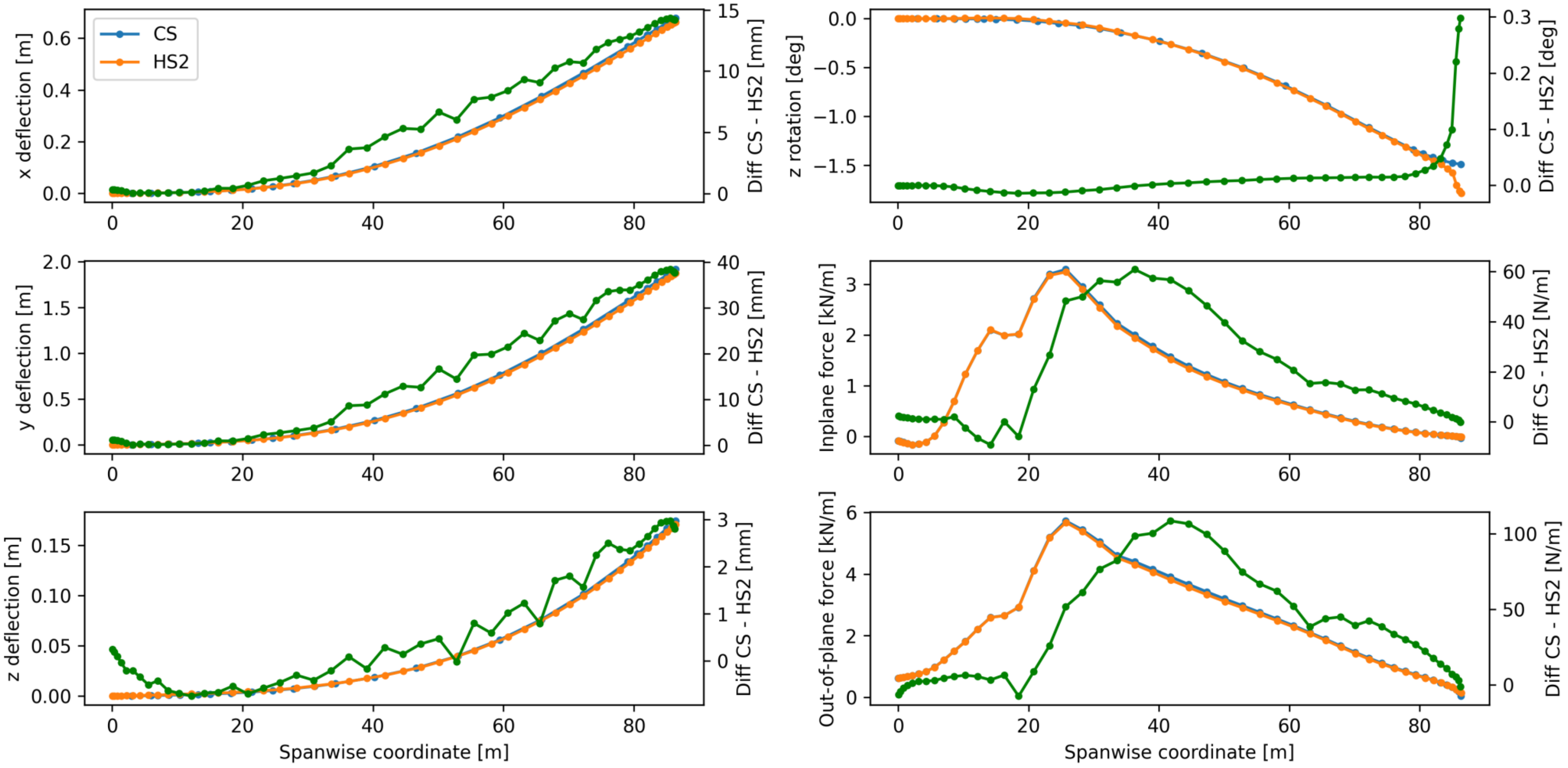
DTU10MW Steady deflection and forces 11 m/s



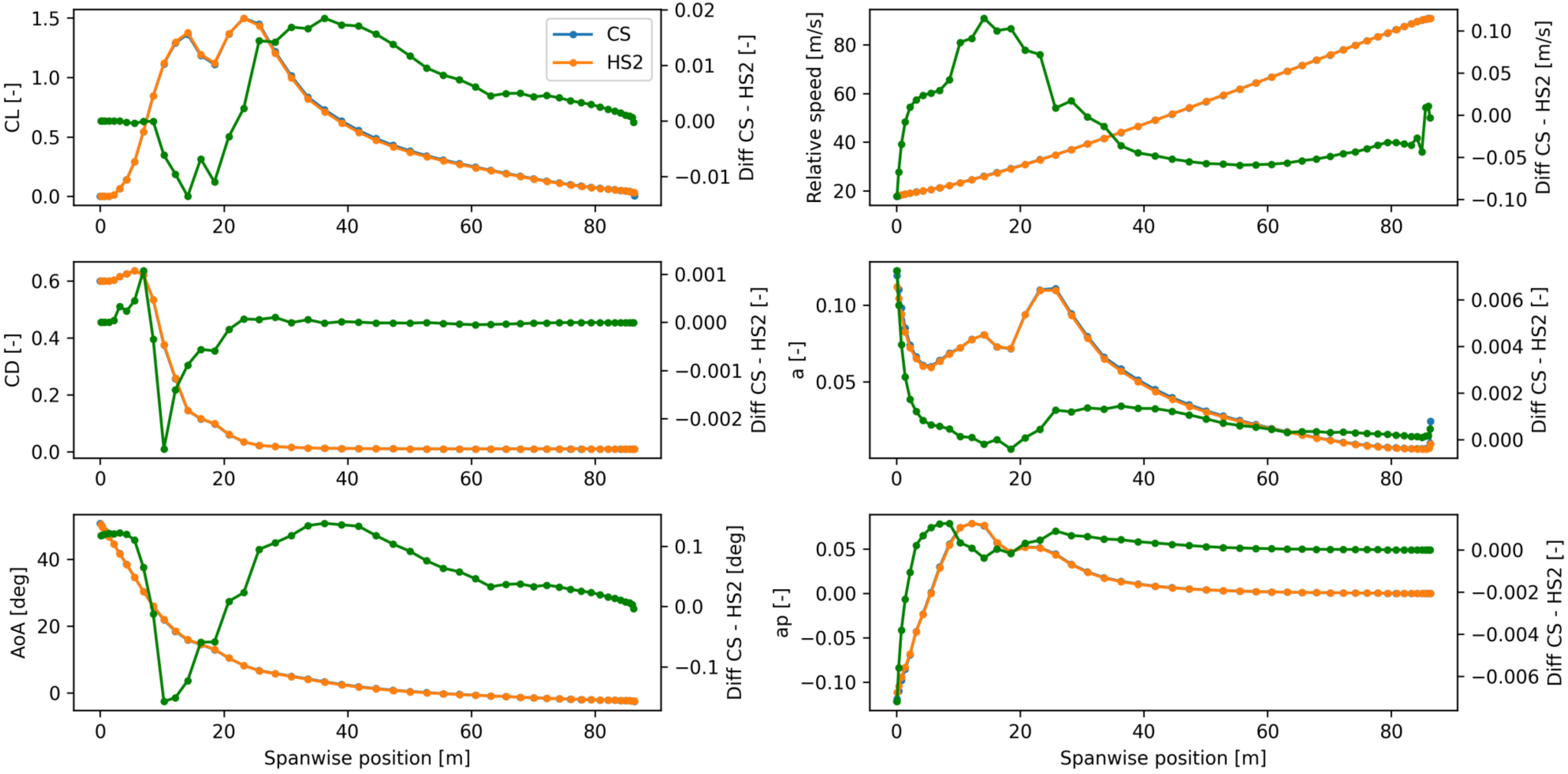
DTU10MW Steady velocity triangle 11 m/s



DTU10MW Steady deflection and forces 20 m/s



DTU10MW Steady velocity triangle 20 m/s



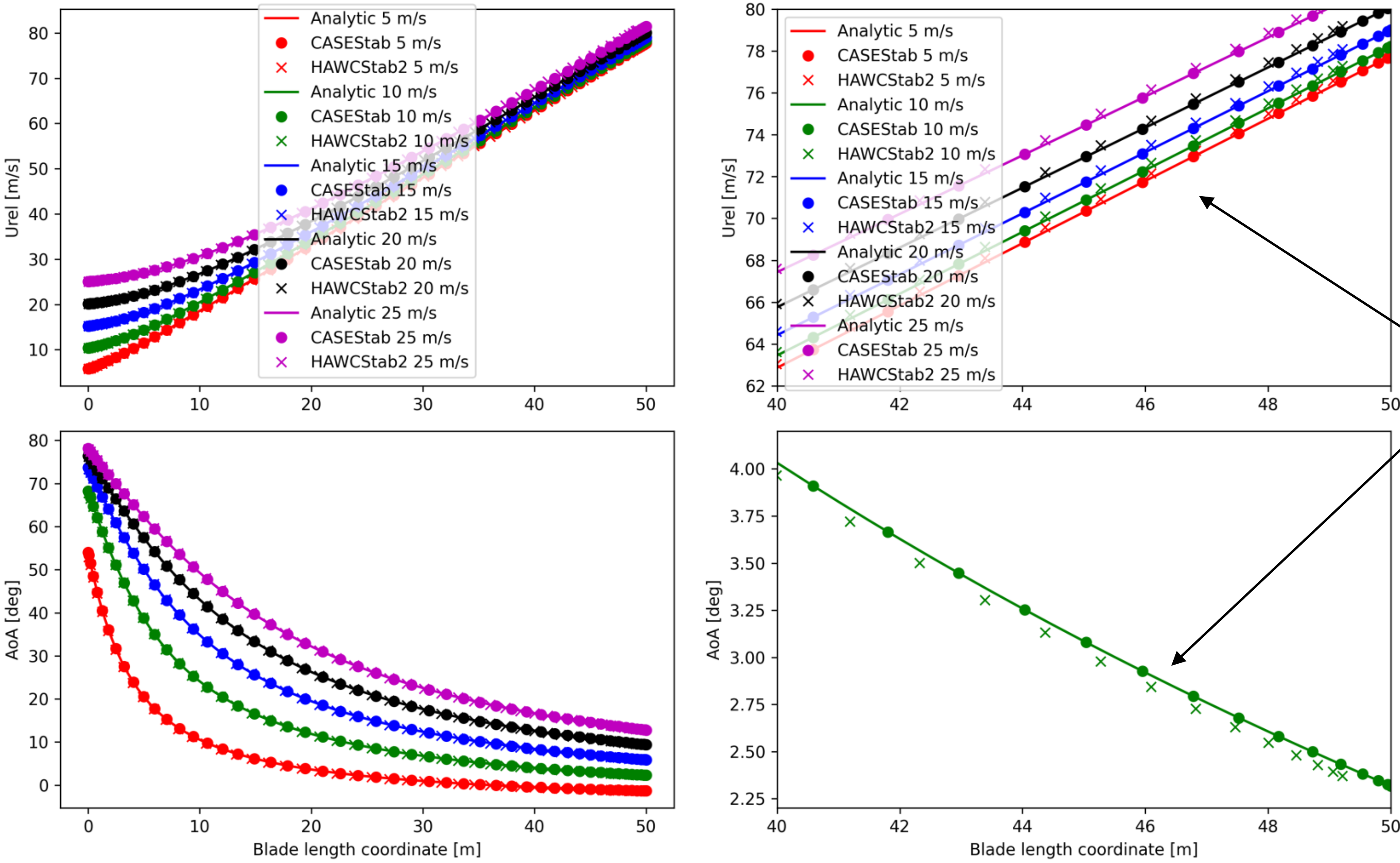
Velocity triangle tests: 50 m straight rigid blade

Rhub = 2 m
Cone = 5 deg
Pitch = 5 deg
Speed (ω) = 14.3 rpm

Analytical solution

$$U = \sqrt{v_x^2 + v_y^2}$$
$$\alpha = \arctan\frac{v_y}{v_x} - 5^o$$
$$v_x = (z\cos(5^o) + 2)\omega$$
$$v_y = V\cos(5^o)$$

Zoom

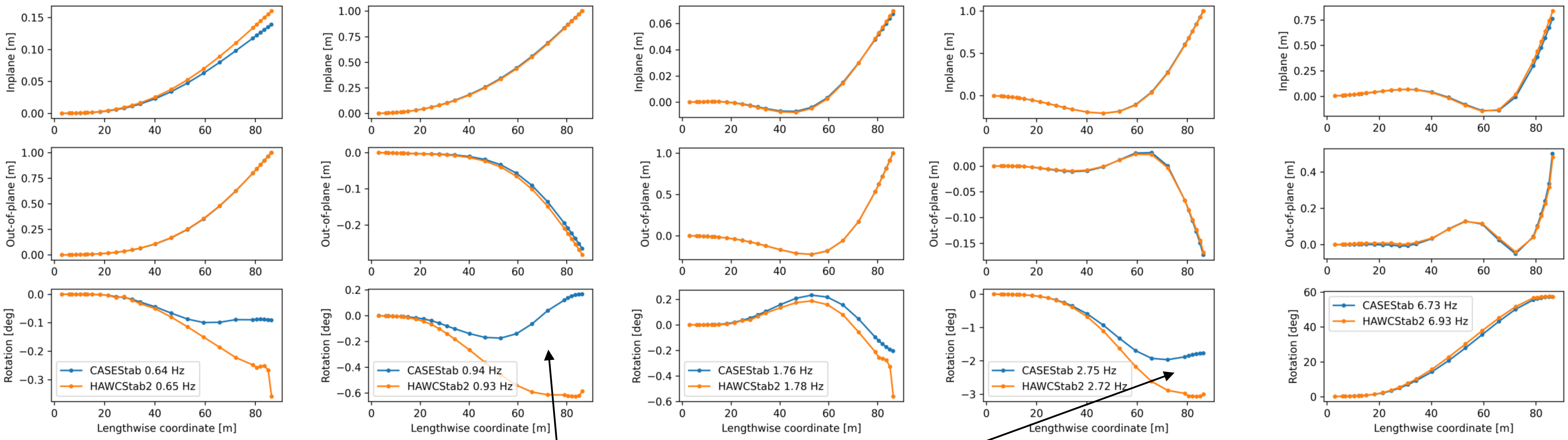


Unexplained differences

DTU10MW blade mode shapes at 11 m/s

Element data directly imported from HAWC2’s export function “beam_output_file_name“

Flap 1 | Edge 1 | Flap 2 | Edge 2 | Torsion 1



Unexplained and serious difference