TurbineX

Aeroelastic Model Verification Manual

IEA Wind 22 MW Reference Wind Turbine

Turbine:	IEA 22 MW RWT (WindIO v1.0.0)
Reference:	Collier et al. (2024) [2]
Solver:	OpenFAST v4.2.0 + ROSCO v2.10
Version:	1.1
Date:	June 21, 2026

TurbineX Engineering Software

1 Scope

This manual benchmarks the TurbineX aeroelastic stack (OpenFAST v4.2.0 + ROSCO v2.10) against the four-code comparison of Collier et al. (2024) [2] on the IEA 22 MW reference turbine [1]. Five quantitative outputs are compared:

- Mass and inertia (§3).
- Structural frequencies and damping for the isolated blade (§4).
- Steady-state operation 3–25 m/s (§5).
- Linear stability analysis (§6).
- Turbulent wind statistics and damage equivalent loads (§7).

Acceptance is by *cross-code spread*: TurbineX lies within the band reported across Bladed, HAWC2, OpenFAST, and QBlade for each quantity. This avoids penalising legitimate solver-to-solver differences while providing a defensible bound. Reference data digitised from figures carries an estimated ±3–5% digitisation uncertainty; table data is exact as printed.

2 Turbine and Setup

Parameter	**Value**
Rated power	22 MW, three-bladed, upwind, direct drive
Rotor diameter	284 m, hub height 170 m
Rated wind speed	11.5 m/s, rated rotor speed 7.84 rpm
Cone / tilt / prebend	4° / 6° / 7 m at tip
Foundation	Monopile, water depth 34 m, rigid at seabed
TurbineX solver	OpenFAST v4.2.0 single precision, ElastoDyn + AeroDyn v15
TurbineX controller	ROSCO v2.10, time step $\Delta t = 0.005$ s
Reference codes	Bladed 4.14, HAWC2 13.0 / HAWCStab2 2.16, OpenFAST 3.5.3, QBlade 2.0.7

Table 1: Turbine and solver configuration. Codes compared in the reference paper.

3 Mass and Inertia

What we check. Total masses and blade mass moments at zero rotor speed. Extracted from the ElastoDyn summary file (`*.ED.sum`) at simulation start. No time-domain run required.

From the UI. Create a Single Simulation, attach the bundled `IEA-22-280-RWT-Onshore` turbine, hit *Run*; the masses appear under *Results* → *Setup summary* as soon as the job is queued.

Property	**Bladed**	**HAWC2**	**OpenFAST**	**QBlade**	**TurbineX**	**Spread**
Blade mass [kg]	8.243e4	8.156e4	8.262e4	8.242e4	TBD	1.3%
Blade 1st moment [kg m]	3.034e6	3.033e6	3.068e6	3.045e6	TBD	1.1%
Blade 2nd moment [kg m^2]	2.048e8	2.052e8	2.049e8	2.059e8	TBD	0.5%
RNA mass [kg]	1.217e6	1.215e6	1.218e6	1.218e6	TBD	0.3%
Tower + monopile [kg]	2.665e6	2.663e6	2.639e6	2.665e6	TBD	1.0%

Table 2: Mass and inertia, cross-code reference (Collier et al. 2024, Table 2). Spread = (max − min)/mean. Pass band: TurbineX within ±2% of cross-code mean.

Pending

TurbineX values pending.

4 Structural Frequencies and Damping — Isolated Blade

What we check. The first eight blade modes (six bending, one torsional, one fourth flapwise) of the isolated blade with rotor locked and pitch = 0°. Frequencies in Hz, damping ratios in %.

From the UI. Run the bundled `IEA-22-280-RWT-VT2` variant (rotor locked, aerodynamics disabled) with a tip-displacement initial condition for each target mode; the free-decay frequency is read from the FFT in the Results tab. Eight short runs.

Mode	Bladed	HAWCStab2	OpenFAST	QBlade	TurbineX	Spread	Pass band
1st flapwise	0.385 (0.49)	0.384 (0.50)	0.386 (0.49)	0.384 (0.51)	TBD	0.6%	±1%
1st edgewise	0.518 (0.51)	0.520 (0.51)	0.520 (0.51)	0.515 (0.51)	TBD	1.0%	±1%
2nd flapwise	1.058 (1.34)	1.060 (1.36)	1.066 (1.34)	1.058 (1.37)	TBD	0.8%	±4%
2nd edgewise	1.486 (1.36)	1.440 (1.29)	1.495 (1.36)	1.483 (1.40)	TBD	3.7%	±4%
3rd flapwise	2.210 (2.75)	2.221 (2.86)	2.229 (2.75)	2.210 (2.83)	TBD	0.9%	±4%
3rd edgewise	3.200 (2.86)	3.121 (2.82)	3.219 (2.86)	3.195 (3.04)	TBD	3.1%	±4%
4th flapwise	3.667 (3.55)	3.744 (4.73)	3.726 (3.55)	3.673 (3.83)	TBD	2.1%	±5%
1st torsional	3.972 (1.90)	3.961 (2.00)	3.981 (1.90)	3.952 (1.90)	TBD	0.7%	±5%

Table 3: Isolated blade modes, Hz (damping % in brackets), reference: Collier et al. 2024, Table 3. Damping ratios reported but not gated — the reference itself shows up to 8.3% disagreement across all modes (29% on 4th flapwise).

Pending

TurbineX values pending.

5 Steady-State Operation 3–25 m/s

What we check. Closed-loop response to uniform inflow at every wind speed from 3 to 25 m/s in 1 m/s steps (23 cases). Tilt = 0°, gravity disabled, support structure rigid — matching Collier 2024 §3.2. Compared channels: rotor speed, pitch, electrical power, rotor torque and thrust, tip-speed ratio, blade tip x / y deformation, blade 80% span rotational deformation, blade root $F_{x,y,z}$ and $M_{x,y,z}$ (15 outputs).

From the UI. Create a *Parametric Analysis* study, attach the bundled `IEA-22-280-RWT-VT3` variant (tilt = 0, gravity off, rigid tower), enable the *Wind speed* sweep axis with (min, max, step) = (3, 25, 1), submit. Reference overlay toggle on the X-Y plot draps the four-code band.

[Figure pending]

`figures/steady_state_xy.png` — X-Y plot from the Results tab: rotor speed, pitch, power, blade root M_y vs wind speed, with the Collier 2024 four-code band shaded and the TurbineX curve overlaid.

Figure 1: Steady-state operation 3–25 m/s.

Pass band. TurbineX value inside the four-code [min, max] band padded ±5% for digitisation, on at least 20 of 23 wind speeds, for each channel. Blade root M_z is one to two orders of magnitude smaller than the other moments and shows similar cross-code spread; for M_z acceptance is by envelope inspection only.

6 Linear Stability Analysis

What we check. Coupled-mode frequencies and damping ratios from numerical linearisation at each operating point (3–25 m/s). Six rotor modes: 1st and 2nd flapwise, 1st torsional, 1st / 2nd / 3rd edgewise. Each mode resolved into collective, forward whirling, and backward whirling components. Stall and dynamic-wake effects included.

From the UI. Create a *Single Simulation* study (linearization is single-only — the Advanced *Linearize* toggle is hidden on parametric and certification flows), pick a wind speed of interest, and enable *Linearize* on the Advanced Settings panel. The platform expands this single toggle into the full set of OpenFAST companion parameters required for a closed-loop linearization — `CalcSteady`, `NLinTimes`, `TrimCase`, `TrimTol`, `TrimGain`, `LinInputs`, `LinOutputs`, `LinOutJac`, `LinOutMod`, and the five ServoDyn modes (`PCMode`, `VSContrl`, `YCMode`, `HSSBrMode`, `AfCmode`) that OpenFAST requires zeroed for linearization. Each operating point produces `*.lin` files that are collected with the rest of the job's artifacts and surfaced as a Campbell diagram under the *Stability* tab of the Results pane. To compare frequencies across wind speeds, run multiple single sims — one per operating point.

Note

Status as of v1.3. Working end-to-end on every bundled reference turbine, including the IEA 22 MW. The platform applies NREL's *runCampbell* recipe (`openfast_toolbox/data/NREL5MW/5MW_Land_Lin_Templates/`) when the user enables *Linearize* on Advanced Settings: generator DOF locked (`ED_GenDOF=False`), no trim (`CalcSteady=False`), quasi-steady aerodynamics (`AD_UA_Mod=0`), controllers disabled (`SrvD_PCMode=SrvD_VSContrl=SrvD_YCMode=SrvD_HSSBrMode=SrvD_AfCmode=0`), and one linearization at `LinTimes = TMax - 1.0` s. The platform's auto-init layer writes a steady-state `RotSpeed` and `BlPitch` into ElastoDyn based on the user-chosen wind speed, the rotor stays at that speed (locked generator), transients decay over the simulation, and OpenFAST writes a combined `.lin` near the end.

Why this works where `CalcSteady=True` did not. The `CalcSteady=True` trim solver requires the simple variable-speed controller's setpoints (`VS_RtGnSp`, `VS_RtTq`, `VS_Rgn2K`) to balance against aerodynamic torque at the operating point. Bundled reference turbines ship ROSCO setpoints that linearization disables, leaving the simple law with non-converging defaults — the rotor motors above rated or trips OpenFAST's periodicity check below rated. runCampbell sidesteps the trim by locking the generator at the auto-init steady-state rpm and letting the structural / aerodynamic transients decay over the simulation time.

Verified results. IEA 22 MW Onshore at 8 m/s: 19 modes, 1st tower fore-aft 0.211 Hz, 1st tower side-side 0.224 Hz, blade flap modes 0.55 Hz, with aero damping in the 0.3–7.8 % range across modes. NREL 5 MW Land at 8 m/s: 15 modes including 1st blade flapwise 1.09 Hz (matching the published value). Both produce real aero-elastic Campbell modes on the standard demo bundles without any special variant.

User contract. Set `simulation_time_s` $\geq$ 60 s (120 s recommended) so transients decay before linearization. Steady wind only (TurbSim rejected at submission — linearization requires deterministic inflow). Single Simulation mode only (the Sweep tab and Certification flow hide the Linearize toggle to prevent multi-OP trim cascades). Sweep wind speed by running multiple Single sims — each contributes one operating-point column to the Campbell diagram on Results.

[Figure pending]

`figures/stability_freq_damp.png` — 12-panel grid: top six panels are mode frequency vs wind speed (1st flap, 2nd flap, 1st torsion, 1st edge, 2nd edge, 3rd edge), bottom six are corresponding damping ratios. Solid = collective, dotted = forward whirl, dashed = backward whirl. Bladed, HAWC2, OpenFAST reference curves overlaid; TurbineX curve in NREL blue.

Figure 2: Linear stability analysis (Collier et al. 2024, Figure 5).

Note

The reference paper notes that QBlade results are not provided for this case and that OpenFAST cannot resolve 3rd-edgewise collective above 15 m/s. TurbineX inherits the same OpenFAST limitation; the reference comparison is restricted to the resolvable subset. Cross-code spread on *frequencies* is modest (single-digit %); spread on *damping* for the 1st flapwise mode is large because that mode is very highly damped — treat with care.

7 Turbulent Wind Statistics

What we check. IEC 61400-1 class B NTM at 7 wind speeds $\{5, 9, 11, 13, 17, 21, 25\}$ m/s, 6 seeds per speed (42 cases), 10-minute realisations. Yaw $= 0°$, shear $\alpha = 0.14$, tower shadow on, tilt 6°, blades and tower flexible. Per realisation: mean / std / min / max, plus DEL on blade root moments using rainflow with $m = 10$, $f_{\text{ref}} = 1$ Hz.

From the UI. Create a *Certification Run* on the standard `IEA-22-280-RWT-Onshore`, IEC class IB / turbulence B, enable DLC 1.1 only with the explicit wind-speed list, seeds = 6, yaw = [0]. Submit. Compare via the DLC Matrix and Fatigue DELs views.

[Figure pending]

`figures/turbulent_stats.png` — nine-panel grid showing mean (solid), $\pm 1\sigma$ (dotted), and min/max (dashed) vs wind speed for: rotor speed, electrical power, pitch, generator torque, blade tip x deformation, blade 80% span rotational deformation, blade root M_x, M_y, M_z. Collier 2024 four-code band shaded.

Figure 3: Turbulent wind statistics, DLC 1.1 class B NTM (Collier et al. 2024, Figure 6).

[Figure pending]

`figures/turbulent_dels.png` — three-panel grid: blade root M_x DEL, M_y DEL, M_z DEL vs wind speed, evaluated at $f = 1$ Hz, $m = 10$. Collier 2024 four-code band shaded.

Figure 4: Damage equivalent loads at blade root (Collier et al. 2024, Figure 7).

Pass band. Mean values within the cross-code band padded $\pm 5\%$. DELs within the cross-code band padded $\pm 10\%$ (the wider pad absorbs digitisation plus the reduced 6-seed sample vs the reference's 18-realisation matrix). Peak (min/max) values reported but not gated — the reference itself flags significant cross-code variation in peaks, especially across controller stacks (ROSCO vs DTU WEC) above rated.

8 Summary

#	Test	Status	Pass band
1	Mass and inertia	Pending	±2% of cross-code mean
2	Isolated blade frequencies	Pending	±1 to ±5% depending on mode
3	Steady-state operation 3–25 m/s	Pending	Within four-code band ±5%, 20/23 ws
4	Linear stability analysis	Pending	Within cross-code band on resolved subset
5	Turbulent statistics and DELs	Pending	Mean ±5%, DEL ±10% vs band

Reproducibility. Each test reproduces from the TurbineX UI on a verified account; bundled reference turbine variants (`-VT2`, `-VT3`) carry the solver overrides required to match the reference setups. Zeph can fill the study configuration from a chat prompt — ask *"set up the IEA 22 MW VT3 benchmark"* or *"set up VT5 DLC 1.1 with the verification matrix"*. No scripting required.

Reference paper. W. Collier et al., *Aeroelastic code comparison using the IEA 22 MW reference turbine*, *J. Phys.: Conf. Ser.* **2767** 052042, 2024. Open access: doi:10.1088/1742-6596/2767/5/052042.

References

References

[1] IEA Wind Task 55, *IEA 22 MW Reference Wind Turbine*, DTU Wind Energy Report E-0243, ISBN: 978-87-87335-71-3, v1.0.0, 2024. `https://github.com/IEAWindTask37/IEA-22-280-RWT`.

[2] W. Collier, D. Ors, T. Barlas, F. Zahle, P. Bortolotti, D. Marten, C. S. L. Jensen, E. Branlard, D. Zalkind, K. Lønbæk, *Aeroelastic code comparison using the IEA 22MW reference turbine*, *J. Phys.: Conf. Ser.* **2767**, 052042, 2024. doi:10.1088/1742-6596/2767/5/052042.

[3] IEC, *IEC 61400-1: Wind energy generation systems — Part 1: Design requirements*, 4th edition, 2019.

[4] NREL, *OpenFAST documentation*, v4.2.0, `https://openfast.readthedocs.io/`.

[5] N. Abbas, D. Zalkind, L. Pao, A. Wright, *A reference open-source controller for fixed and floating offshore wind turbines*, *Wind Energy Sci.* **7**, 53–73, 2022, `https://rosco.readthedocs.io/`.