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A VorLap–QBlade Bridge for Design-Level Parked-Load Assessment of Vortex-Induced Vibration

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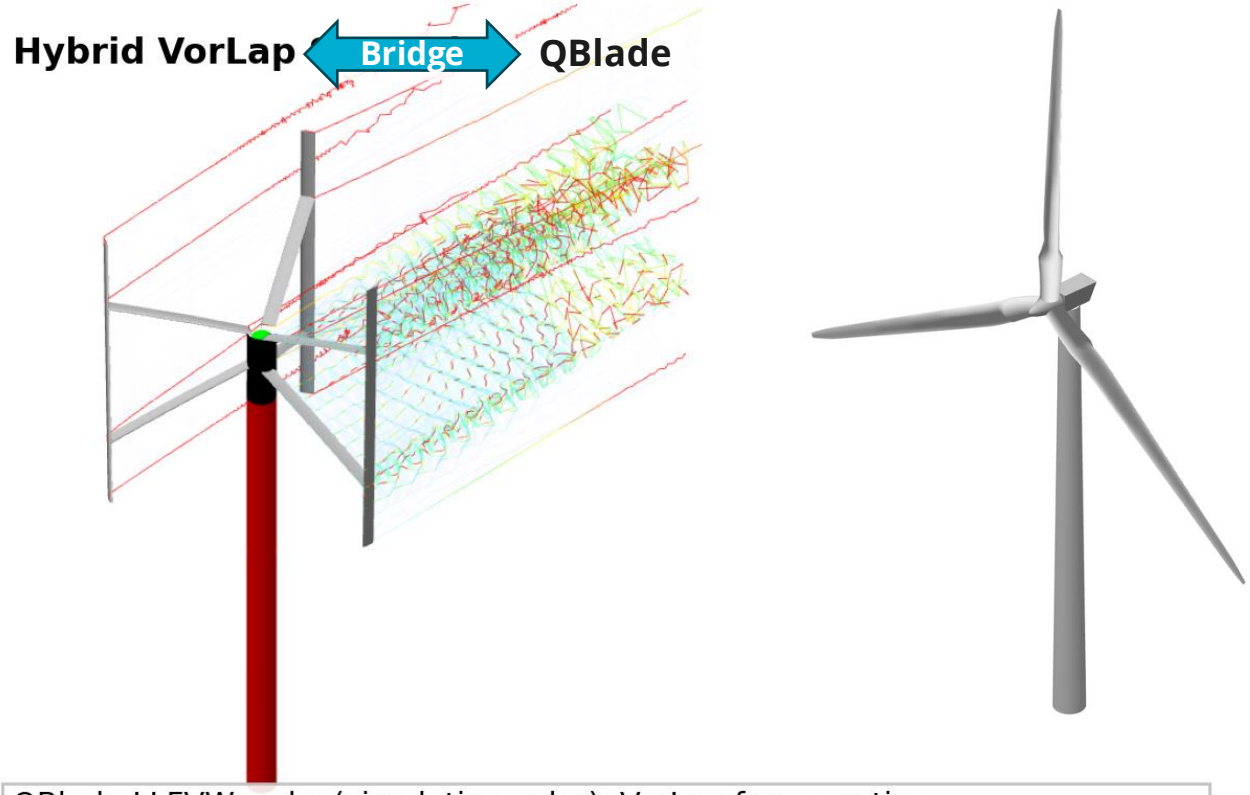
SAND2026-26672C

Presentation Roadmap – Bridge/Coupling

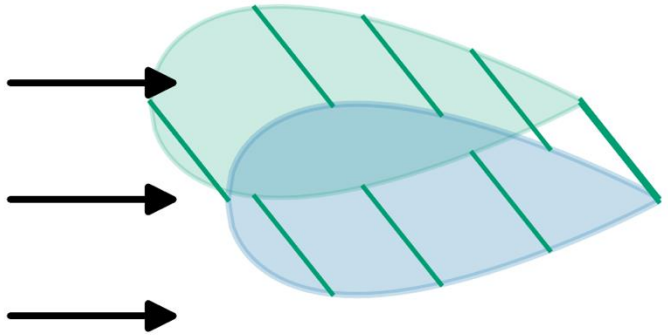
- *Three-part Model*
- *Machine Learning Training*
- *Example H-VAWT*
- *Conclusions and Next Steps*



QBlade LLFVW wake (circulation color); VorLap forces active
U = 7.25 m s^{-1}; 1 RPM; t = 3.5250 s; negative-damping nodal force = 0.110 N

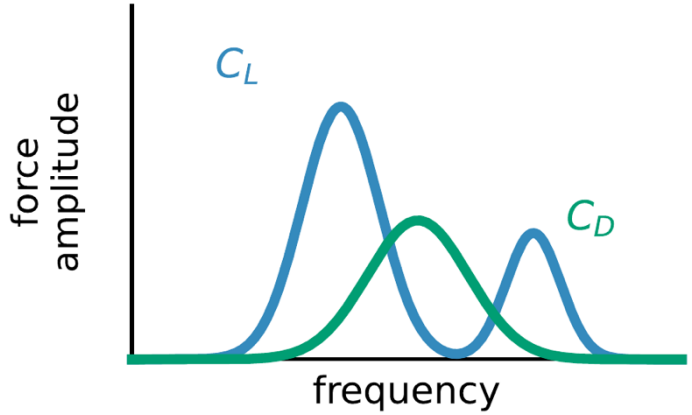
Three-Part Model

QBlade



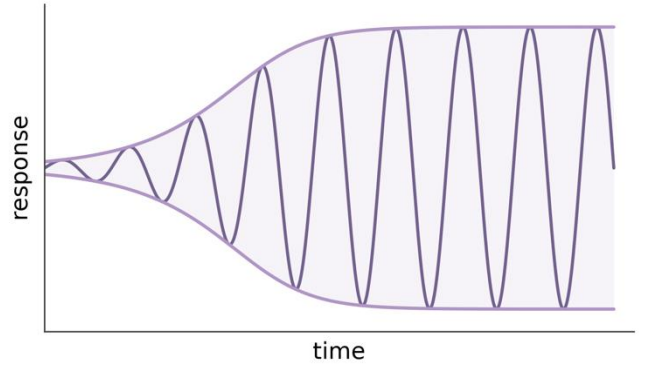
Native aerodynamics
Turbulence and motion

VorLap spectra



Scaled lift and drag
Residual harmonic forces

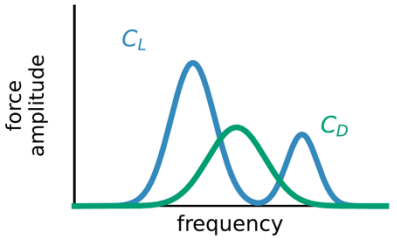
Negative damping



Motion-correlated force
Growth and saturation

Native QBlade + residual spectral + negative-damping forces

SPECTRAL AIRFOIL SIMULATIONS



Kynema-UGF, IDDES

~24M Hexahedral Cells

335 points around airfoil

1m Chord

50 Chords Farfield

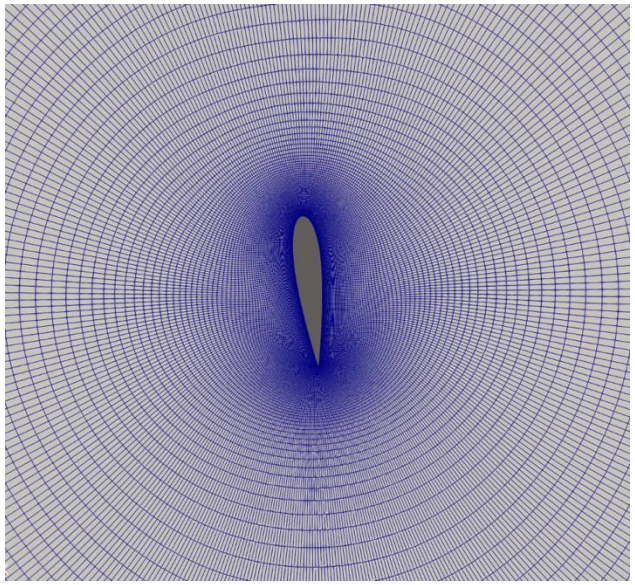
0.125m max expansion

3.75 m/s, Re=250K

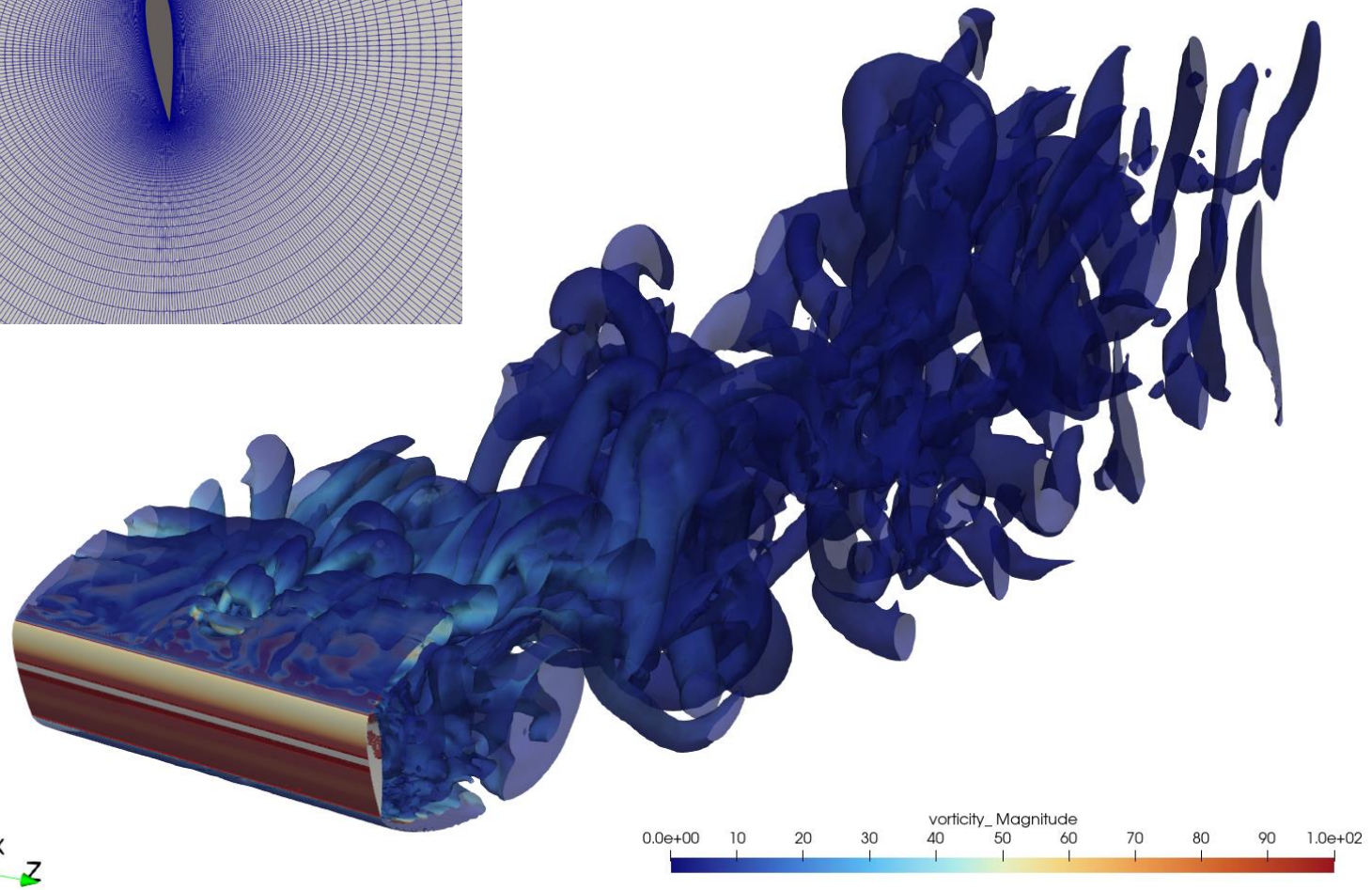
4 Chords' Span

Aoa: 0-360 deg x 4 deg

Y_{wall}=0.000041m

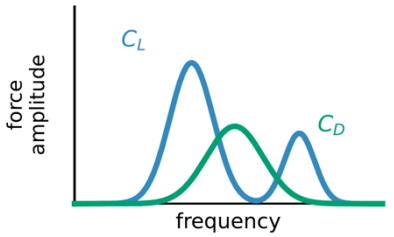


Near-airfoil mesh at Aoa=84 degrees

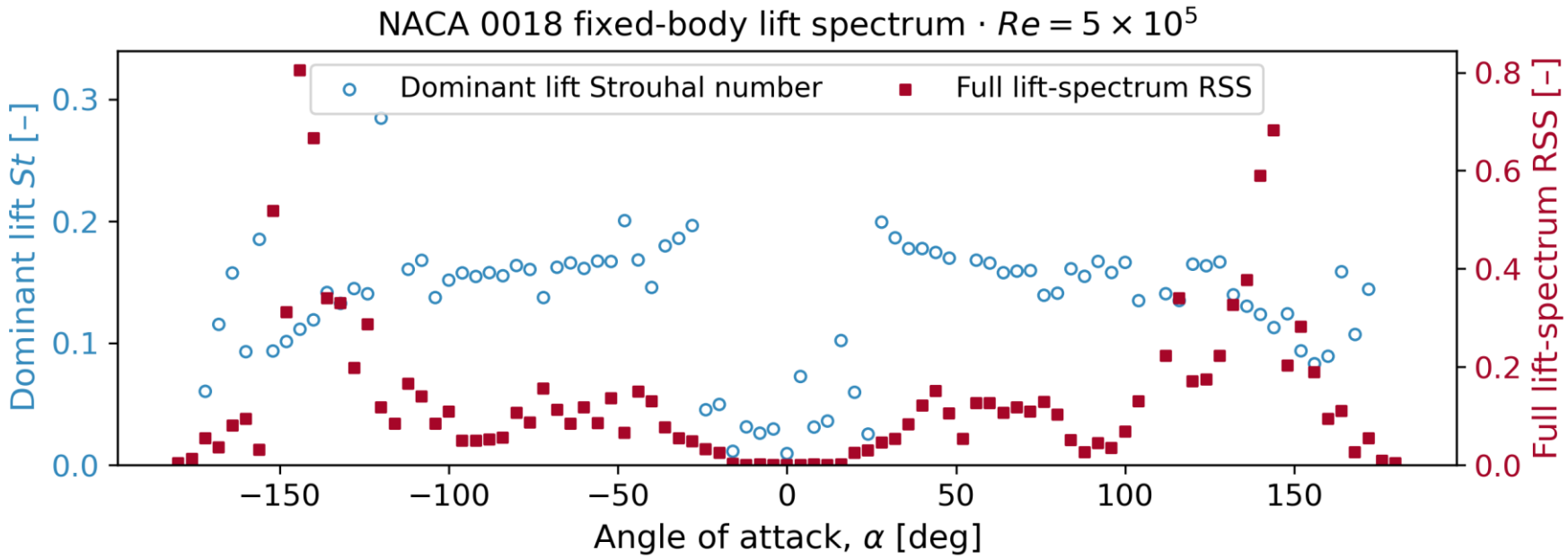


Contour of q-Criterion=1.0 colored by vorticity magnitude, Aoa=84 degrees

VorLap Spectral Bluff Body Loads



Full lift-spectrum RSS = $\sqrt{(\Sigma\ |\hat{C}_{L,k}|^2)}$, $k > 0$

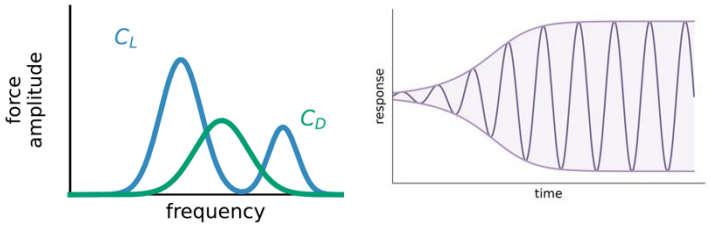


$$f = St\ U_a\ /\ D_{St}$$

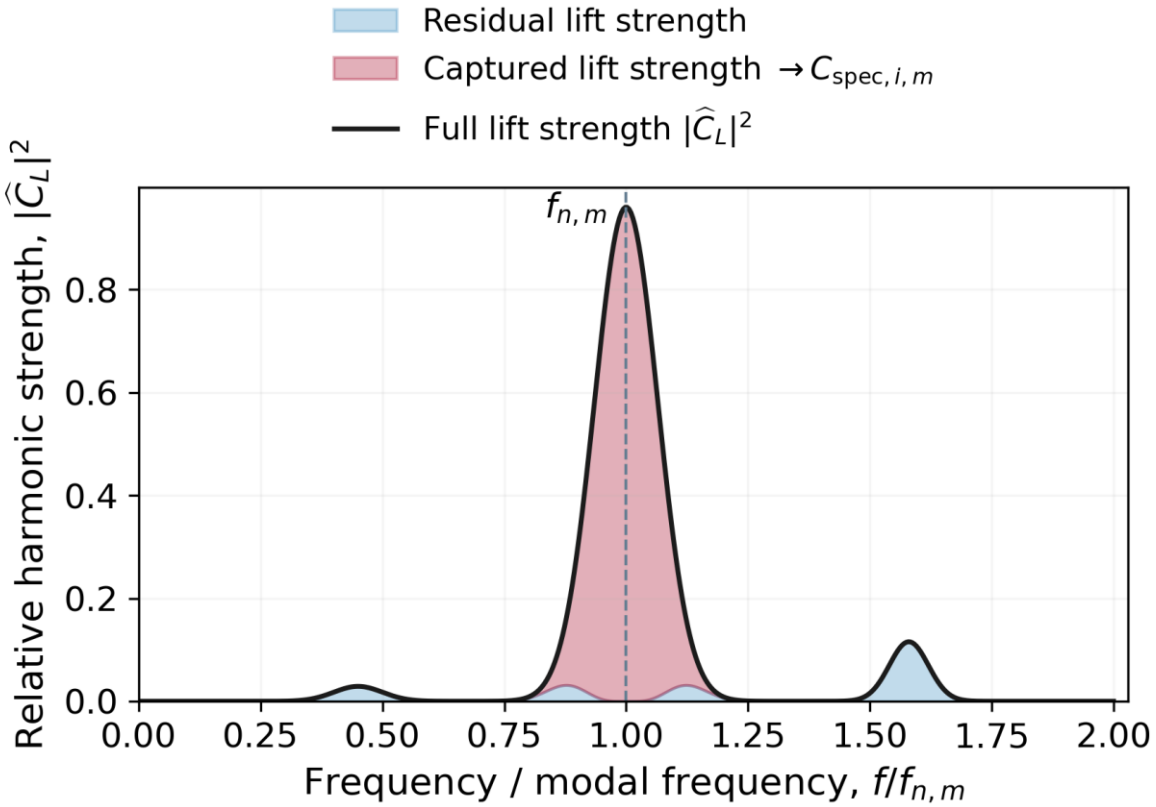
$$|\hat{F}| = \tfrac{1}{2}\ \rho\ U_a^2\ c\ \Delta s\ |\hat{C}|$$

$D_{St} = c \max(|\sin \alpha|, t/c)$ U_a: spectral-query speed $c\ \Delta s$: represented area

Spectra → Negative Damping



(a) Split the full lift spectrum



(b) Build the damping scale

Captured lift coefficient $C_{spec,i,m}$
Root-sum-square of captured harmonics

↓

Flow + geometry + modal weighting
Modal damping basis $B_{spec,m}$ [N s/m]

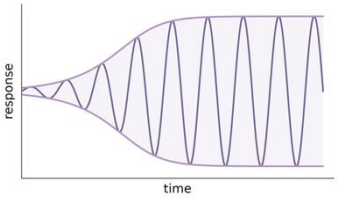
↓

Calibrated gain H × $B_{spec,m}$
Negative-damping model → force Q_m

$$C_{spec,i,m} = [\sum_k \eta_{i,k,m} |\hat{C}_{L,i,k}|^2]^{1/2}$$

$$B_{spec,m} = \sum_i \tfrac{1}{2}\rho U_{a,i} c_i \Delta s_i C_{spec,i,m} \gamma_{i,m} p_{i,m}^2$$

Negative Damping Model



$$Q_m = H\,B_{spec,m}\,\dot{q}_{f,m} - H\,B_{spec,m}\left[\hat{A}_m / (\Lambda\,L_{ref,m})\right]^2 \dot{q}_{f,m}$$

Growth

Amplitude limit

H: machine learned gain

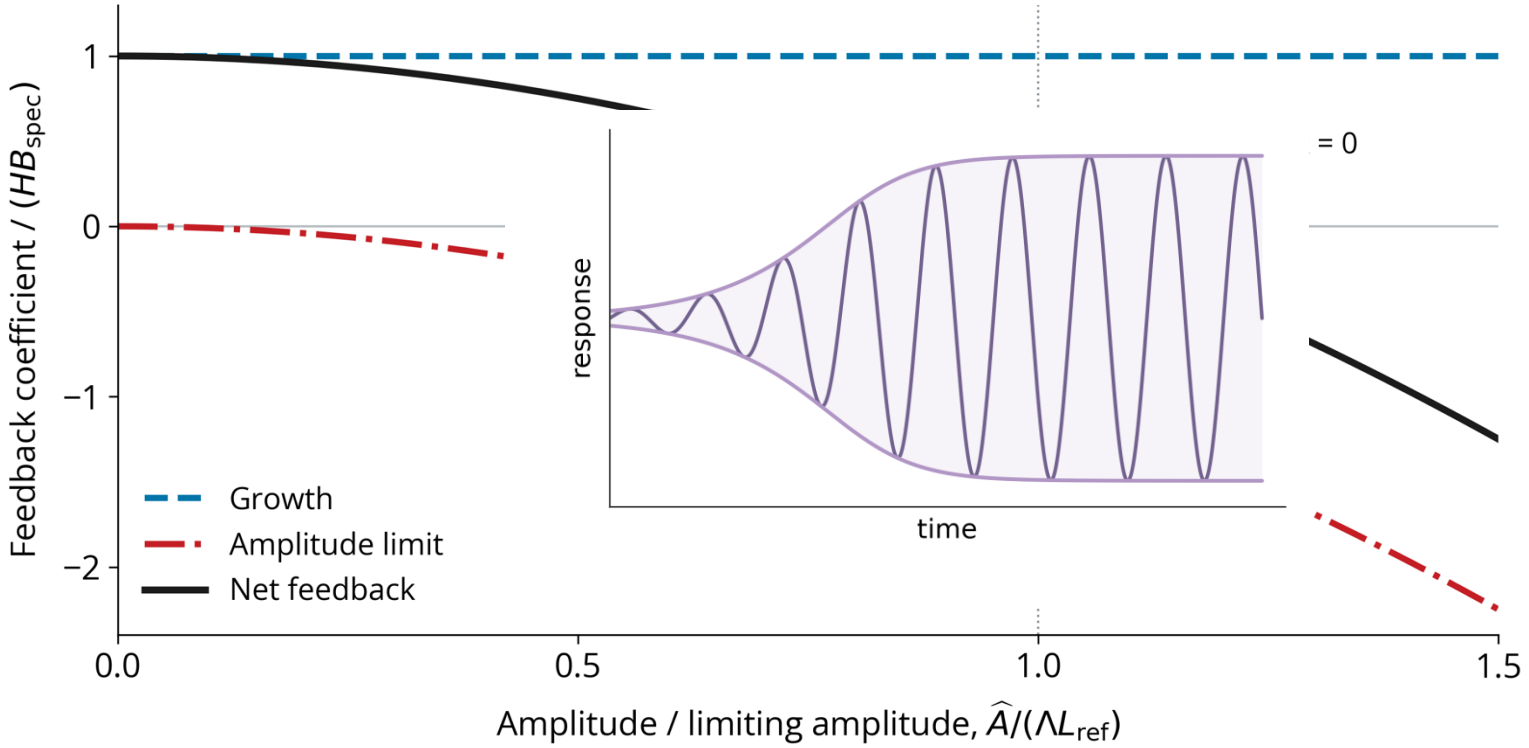
Λ: machine learned amplitude ratio

$B_{spec,m}$: modal damping basis [N s/m]

$\hat{A}_m$: live amplitude estimate

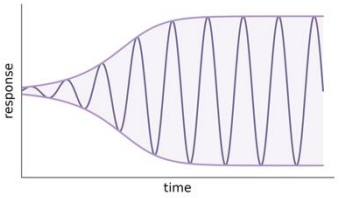
$L_{ref,m}$: reference length

$\dot{q}_{f,m}$: filtered modal velocity

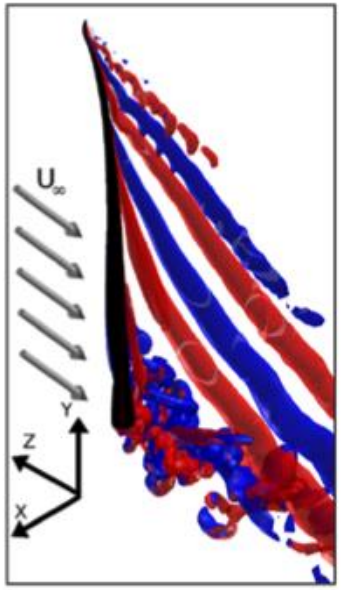


At the limiting amplitude, growth and the amplitude correction cancel

Calibration and training use separate datasets

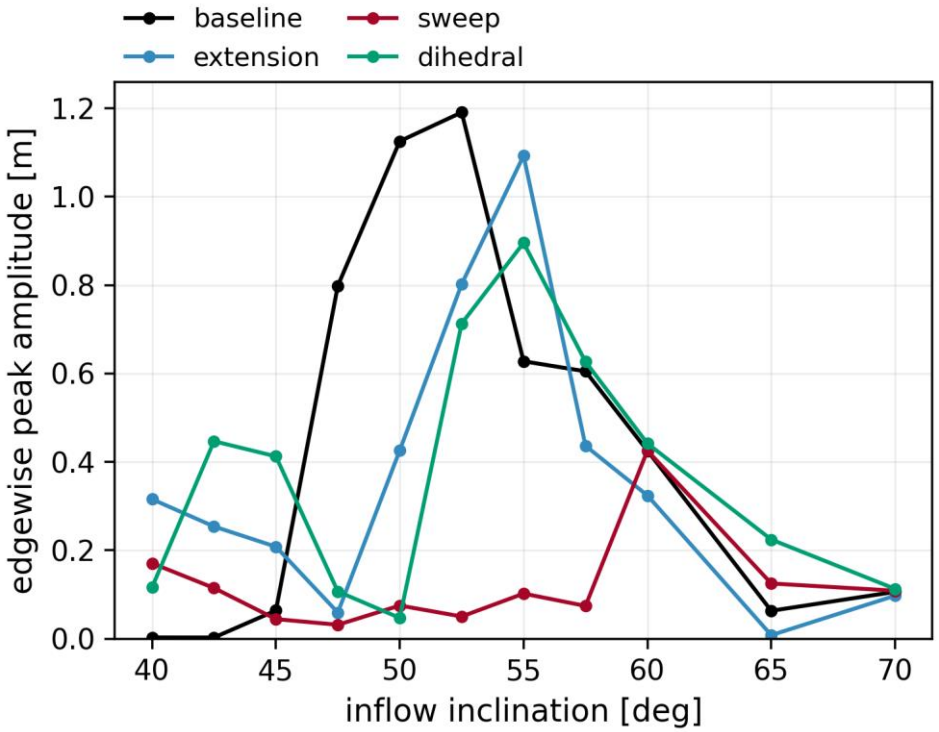


Example Visualization (Horcas 2020)

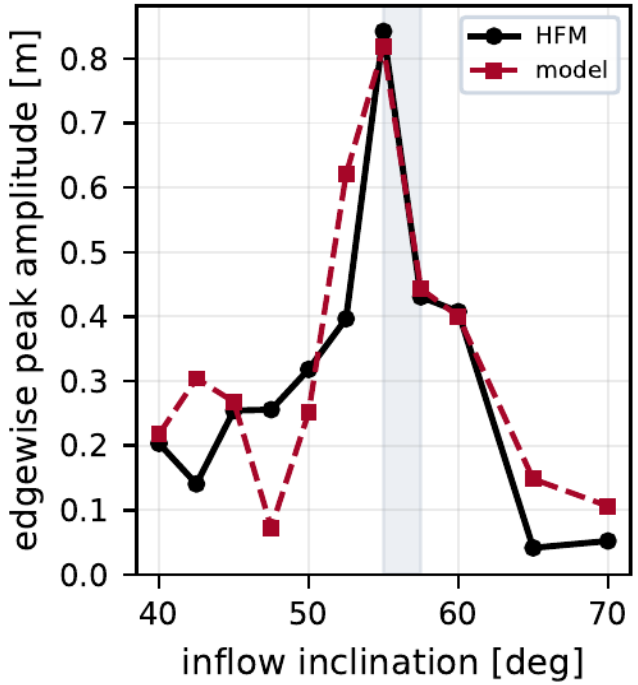


H, Λ calibration

Four tip families → blade-response map

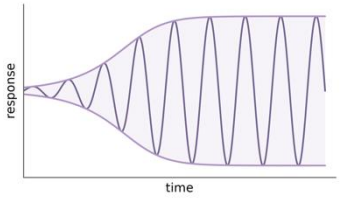


Cross-Validation / Holdout



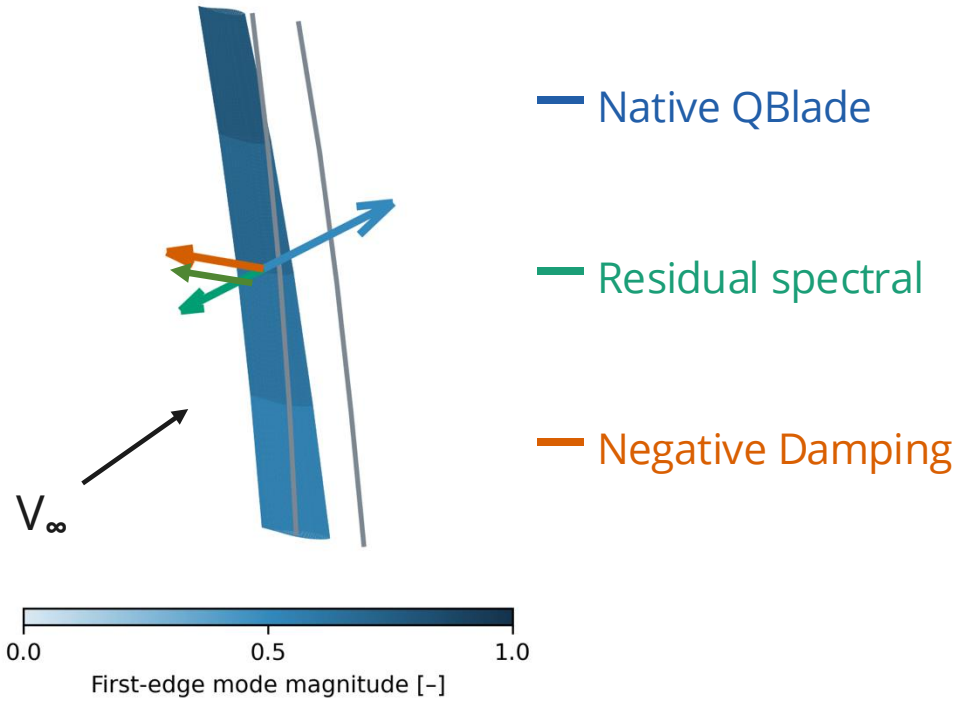
12.9% curve NRMSE
2.84% peak-amp error

Complete-Bridge Training Reproduction



IEA 10-MW single blade · P80A310 · Fu et al. (2026)

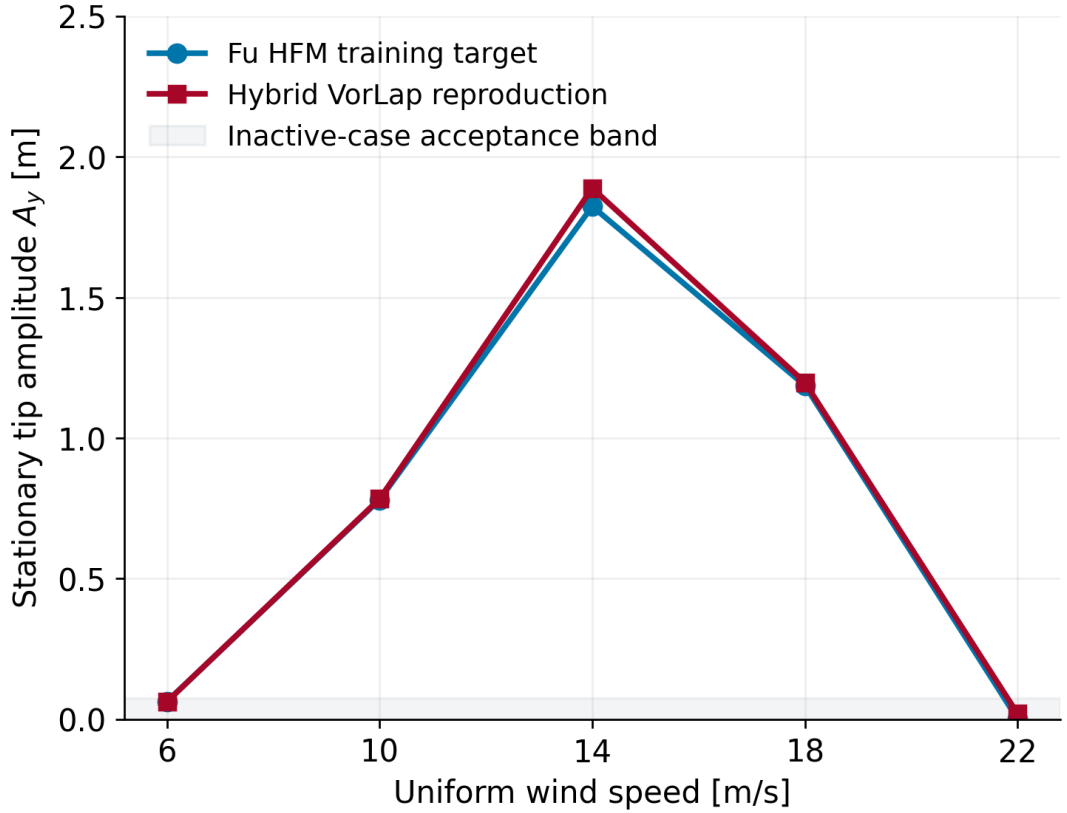
(a) Outer-blade detail at 14 m/s



80–93% blade span · schematic arrows

A_y = 1.889 m · QBlade first-edge reconstruction

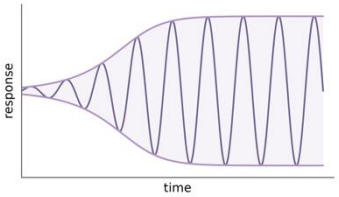
(b) Five-speed training/reproduction



Training reproduction: four active amplitudes agree within 0.41–3.54%

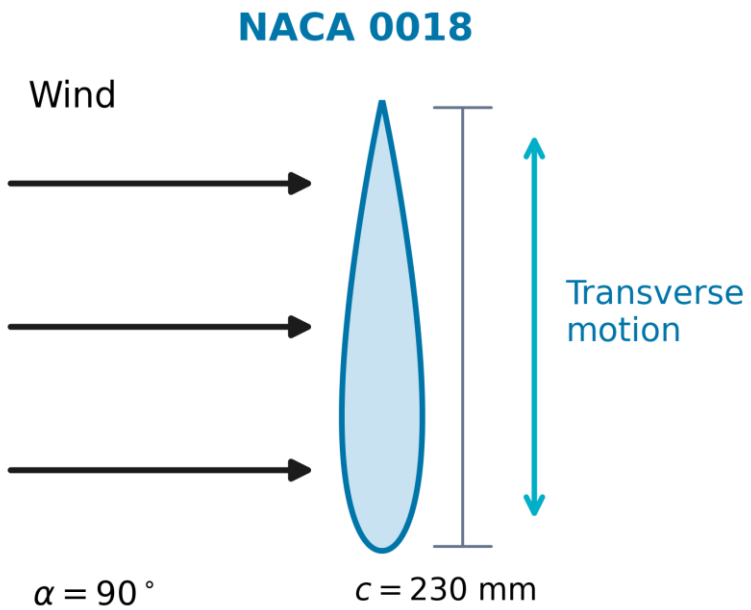
Fu et al. (2026), J. Fluids Struct. 143, 104537 · DOI 10.1016/j.jfluidstructs.2026.104537

No H-VAWT Specific Training, Use Closest



Ehrmann et al. (2014): NACA 0018 section at 90° incidence

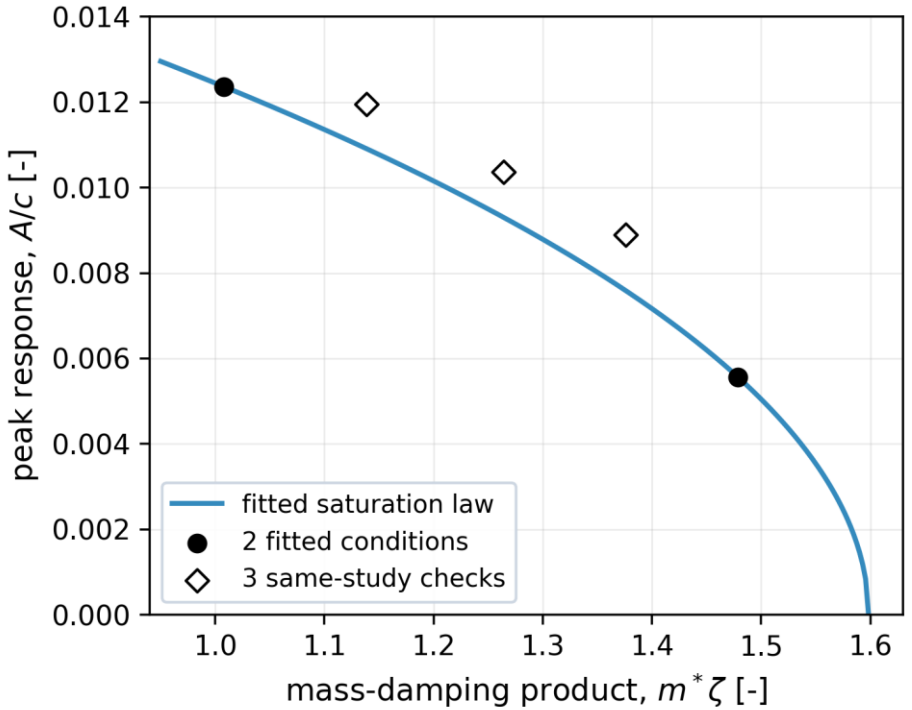
Reported test configuration



Elastic mounting; $f_n \approx 6$ Hz

Test-configuration schematic

H, Λ calibration



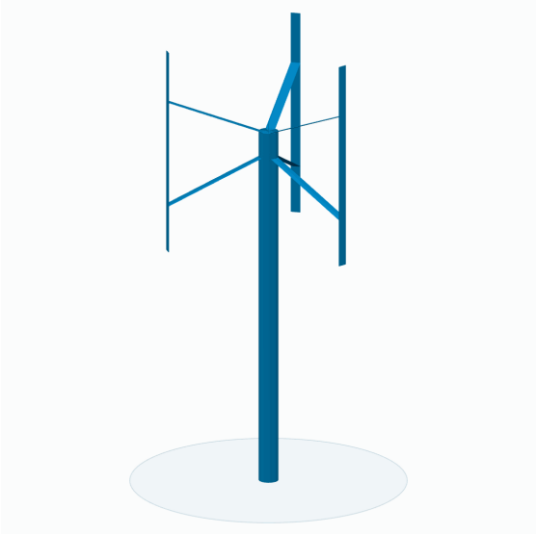
Ehrmann et al. (2014), J. Fluids Struct. 44, 205–215 · DOI 10.1016/j.jfluidstructs.2013.10.008

Three-Part Model -> Three-Part Comparison

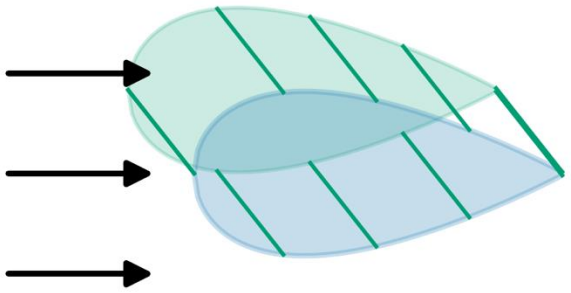
10-m-class H-VAWT · 1 RPM prescribed idling

(11 speeds × 3 seeds + one 50-m/s case) × 3 models = 102 runs

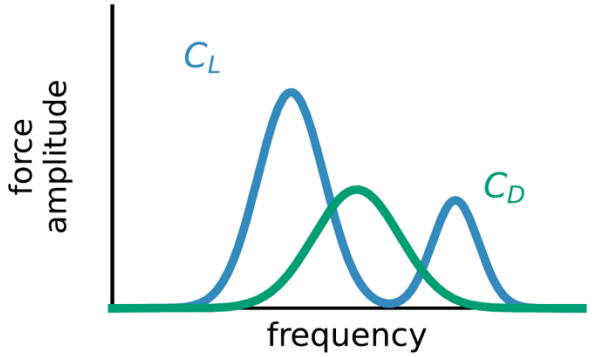
660 s per run; retain 600 s after startup; Δt = 0.0075 s



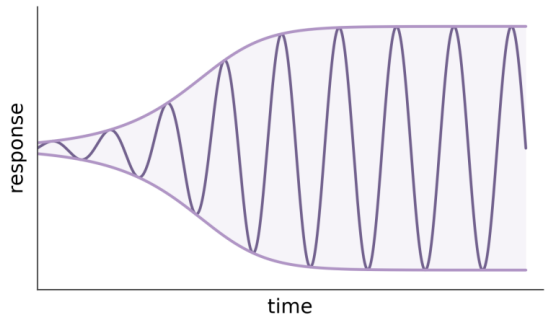
QBlade



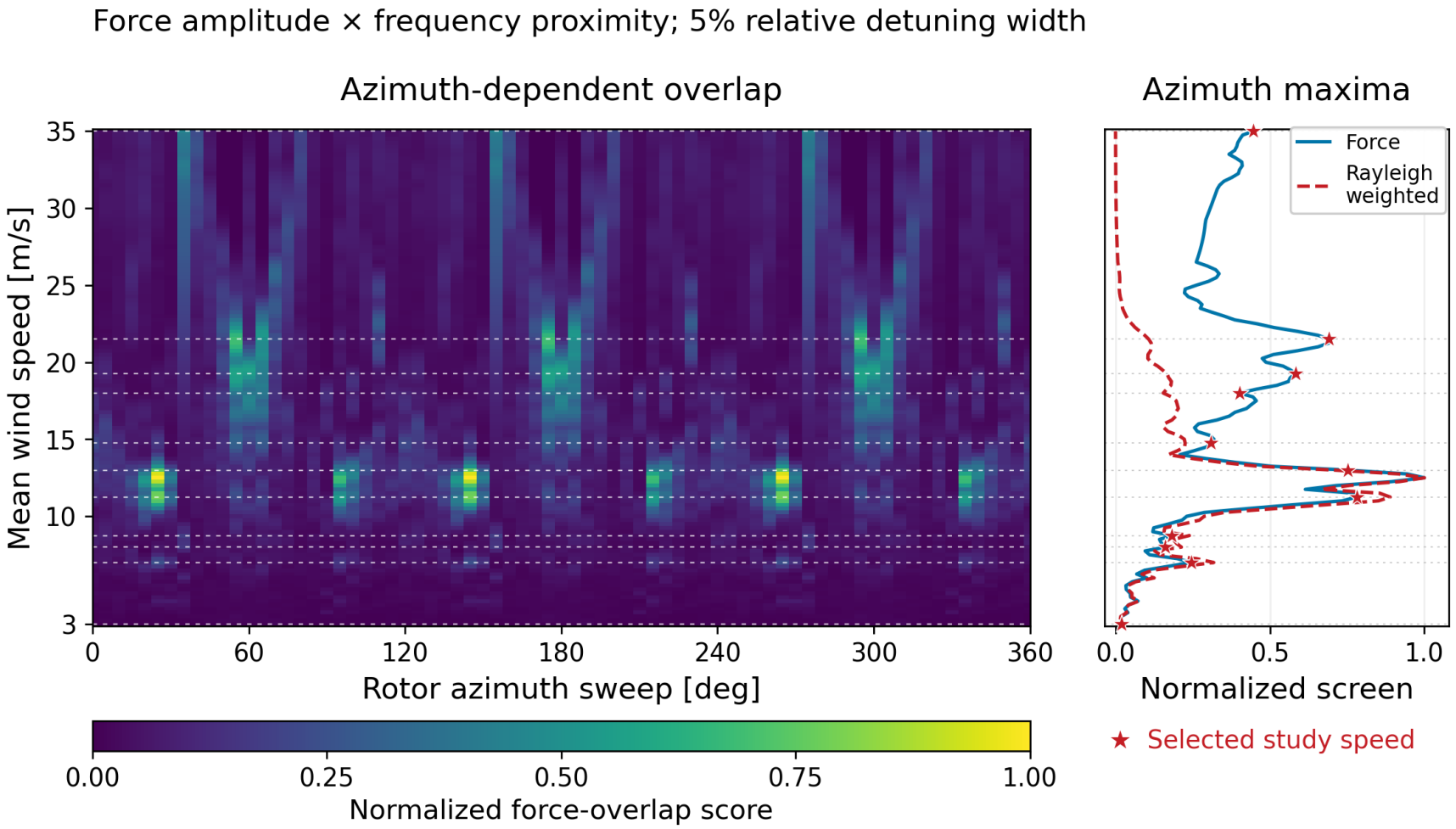
Spectral VorLap



Hybrid VorLap



Select Wind Speeds Where Overlap Occurs

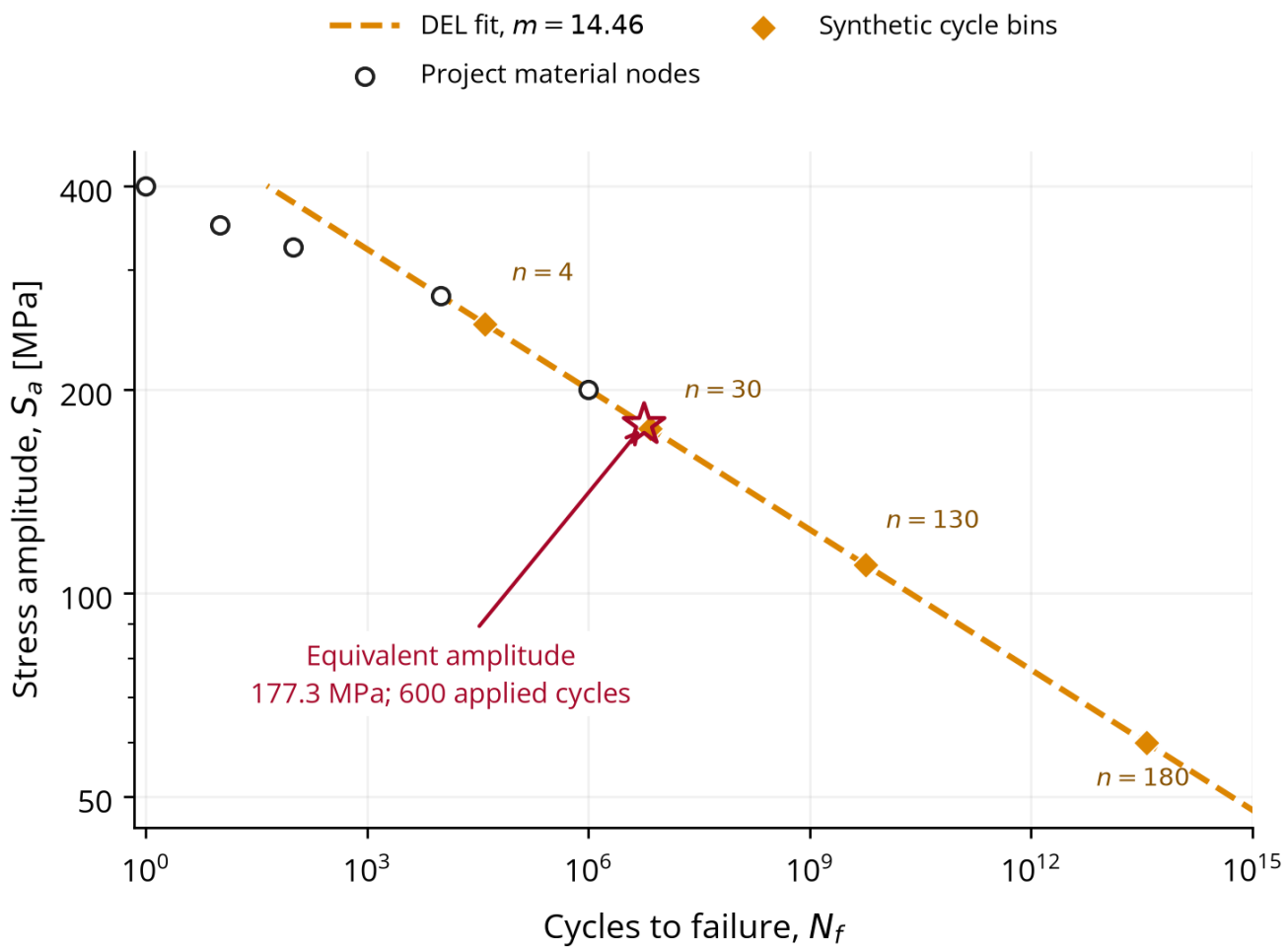


11 wind speeds

3, 7, 8, 8.75,
11.25, 13, 14.75,
18, 19.25, 21.5, 35 m/s

50 m/s: separate extreme-wind case

The S–N Curve Defines the Equivalent Load (DEL)



Miner damage

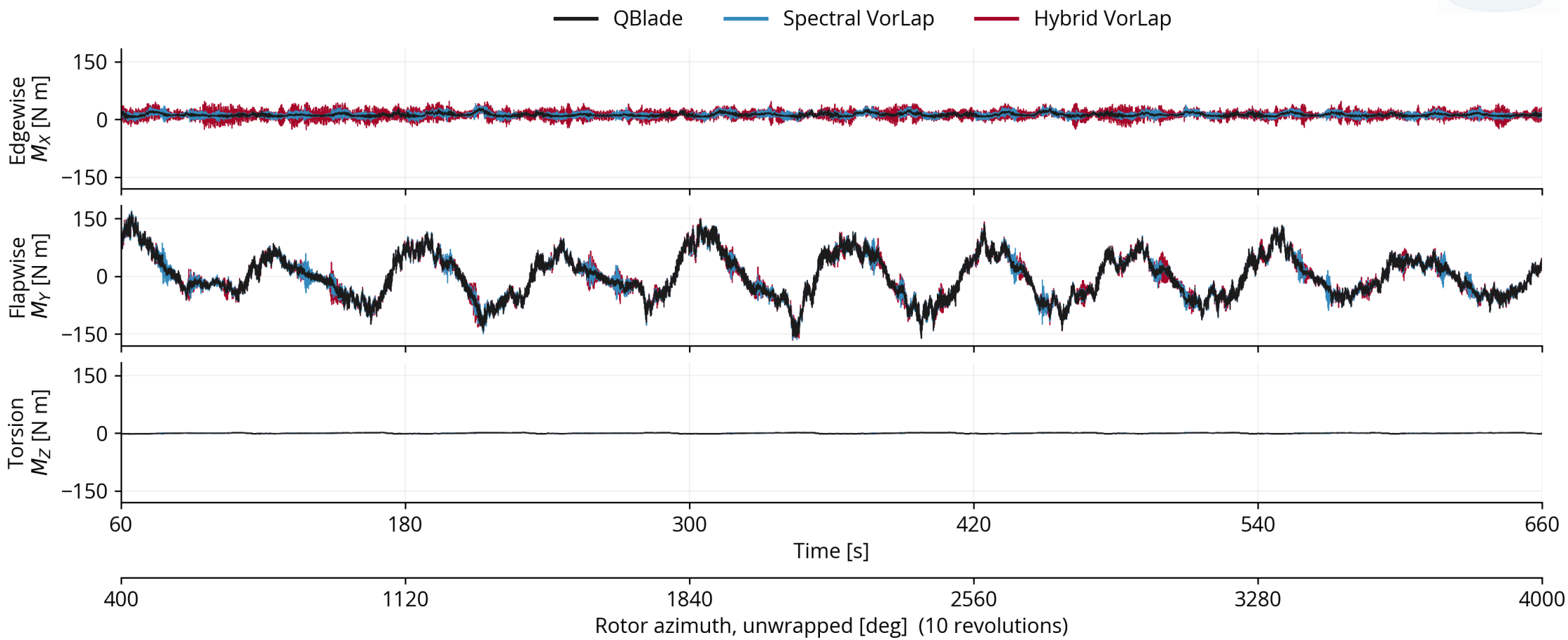
$$D = \Sigma\, n_j \,/\, N_f(a_j)$$

$$D = N_{eq} \,/\, N_f(\Delta\sigma_{DEL} \,/\, 2)$$

Solve for $\Delta\sigma_{DEL}$

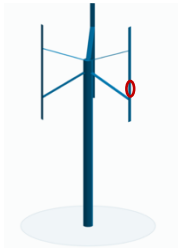
Dashed: two-point High_Roving power law, m = 14.46 · synthetic DEL example

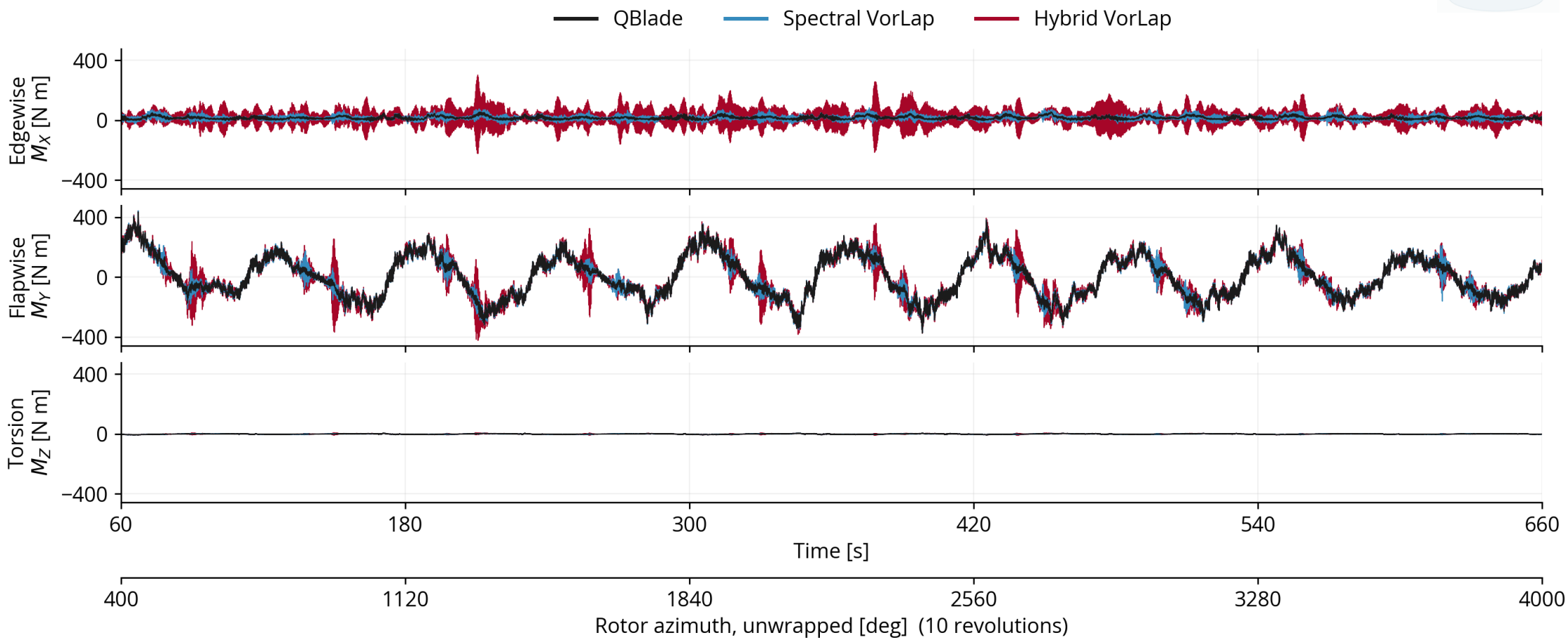
7 m/s — Full 10-Minute Moment History



7 m/s · Blade 1, 23% height · seed 4433456 · 60–660 s · 10 revolutions

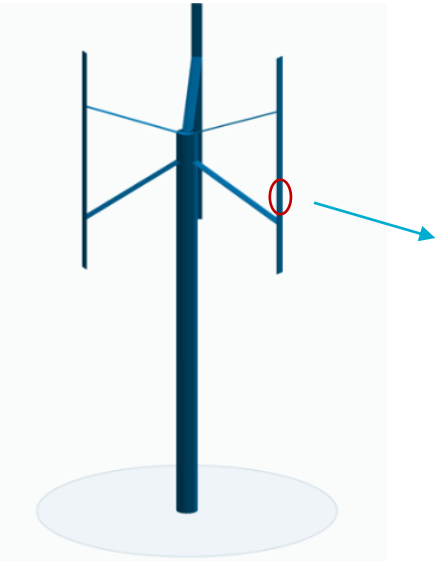
11.25 m/s — Full 10-Minute Moment History

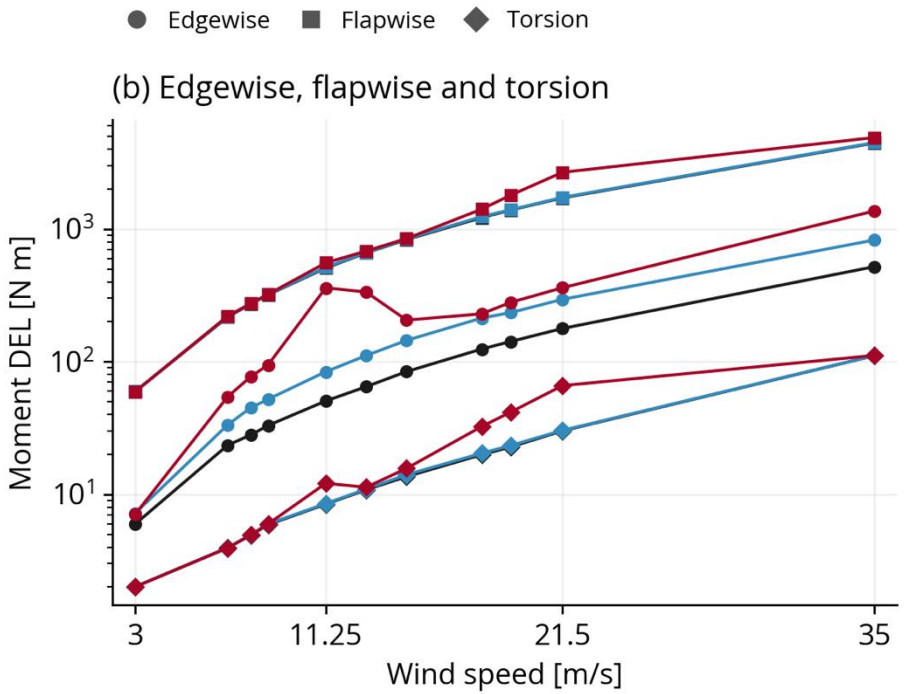


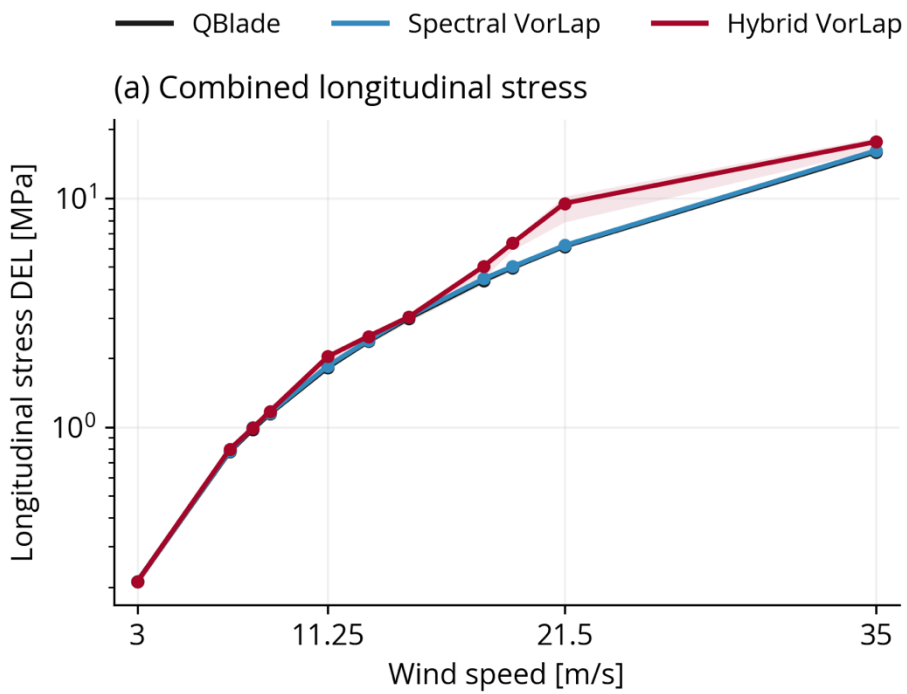


11.25 m/s · Blade 1, 23% height · seed 4433456 · 60–660 s · 10 revolutions

Component DEL and Longitudinal Stress



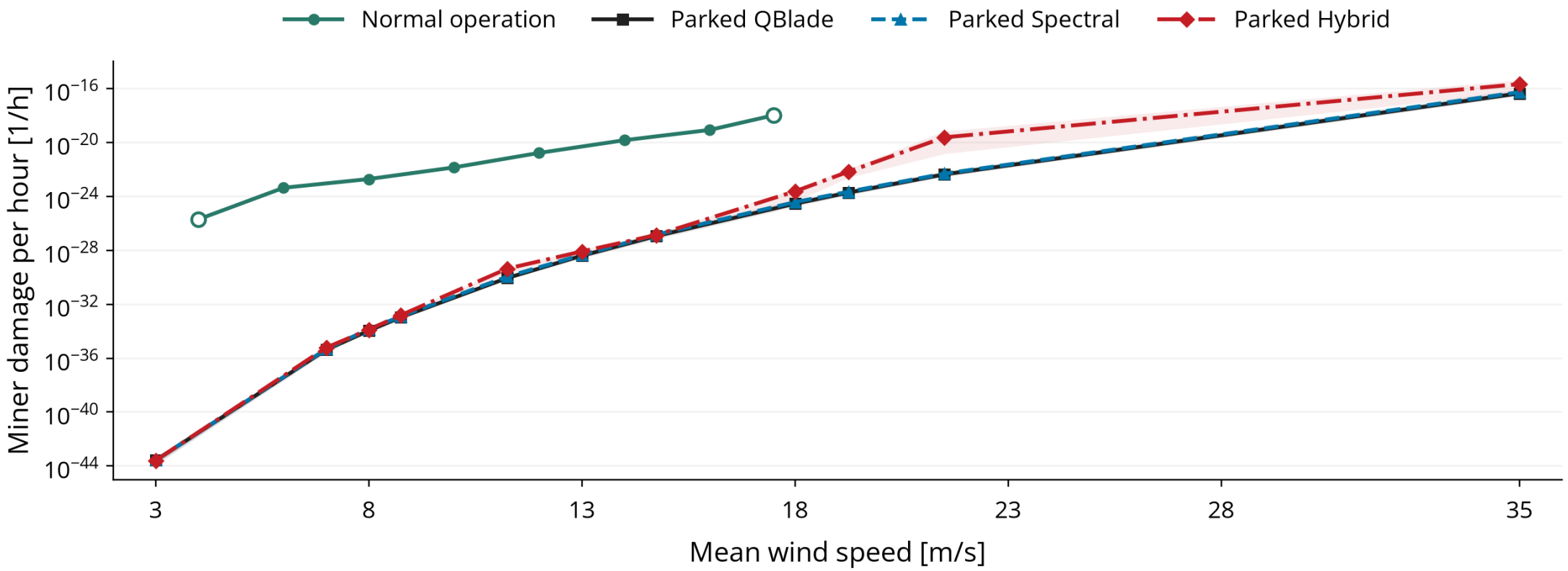




Blade 1, 23% height · lower face x/c = 0.30 · longitudinal = axial + edgewise + flapwise stress

Damage per Hour: Operating and Parked

Blade 1, 23% height · lower face at x/c = 0.30

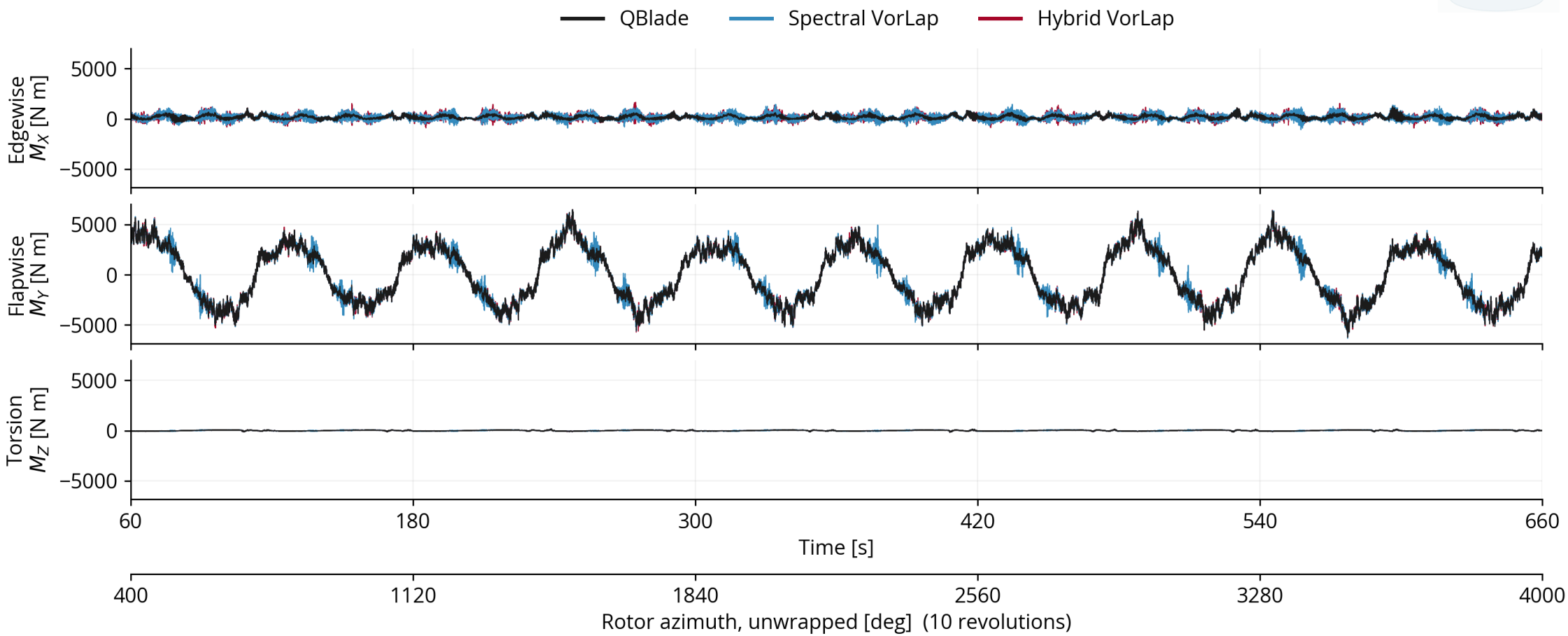


20-year sensitivity: m = 10 · 98% operating availability

Operating 2.46E-10 · Operating + parked Hybrid 3.11E-10 -> 1.26x

Plot: m = 14.46 · loads ×1.35 · material capacity ×0.50 · common mean-stress correction

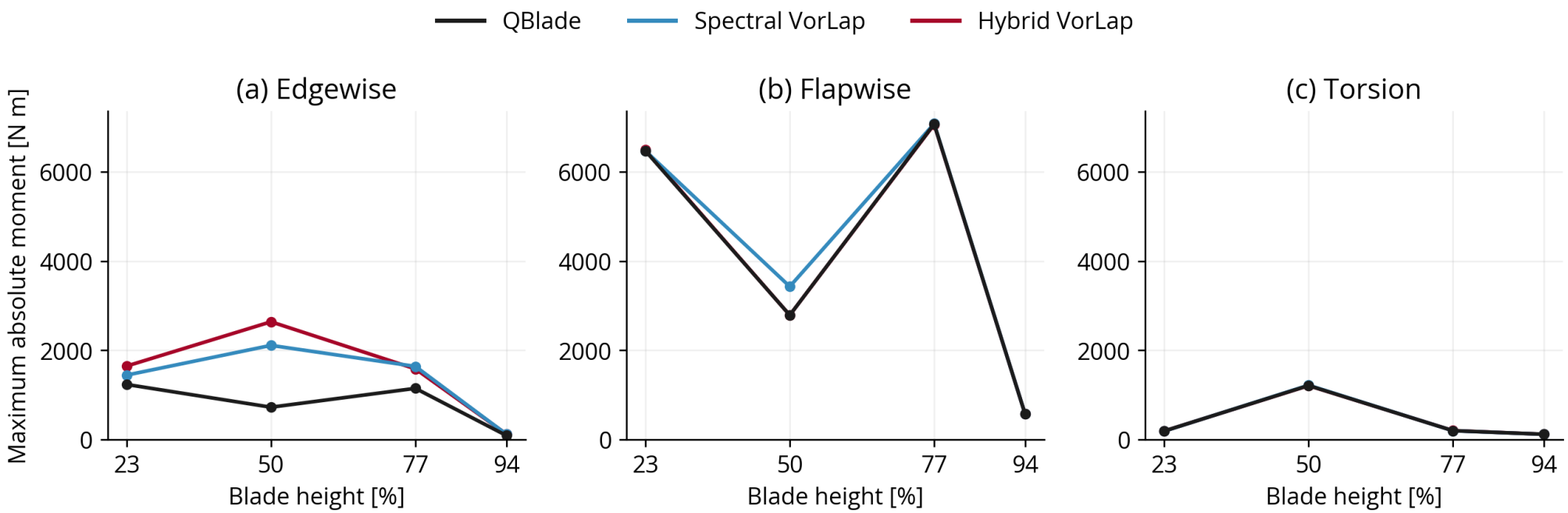
50 m/s — Full 10-Minute Moment History



50 m/s · Blade 1, 23% height · seed 5533456 · 60–660 s · 10 revolutions

50 m/s: Loads and Longitudinal Strength

1EWM50 · 1 rpm · four Blade 1 stations



Minimum Longitudinal Ultimate Safety Factor

QBlade	Spectral VorLap	Hybrid VorLap
7.88	**7.84**	**7.83**

$S_L = \min(X_t/\sigma_{t,max}, X_c/|\sigma_{c,min}|)$ · combined axial and bending stress

VIV Engineering Model: Built

Parked: Hybrid vs QBlade

8.12×

Parked Fatigue damage

3–18 m/s

+0.63%

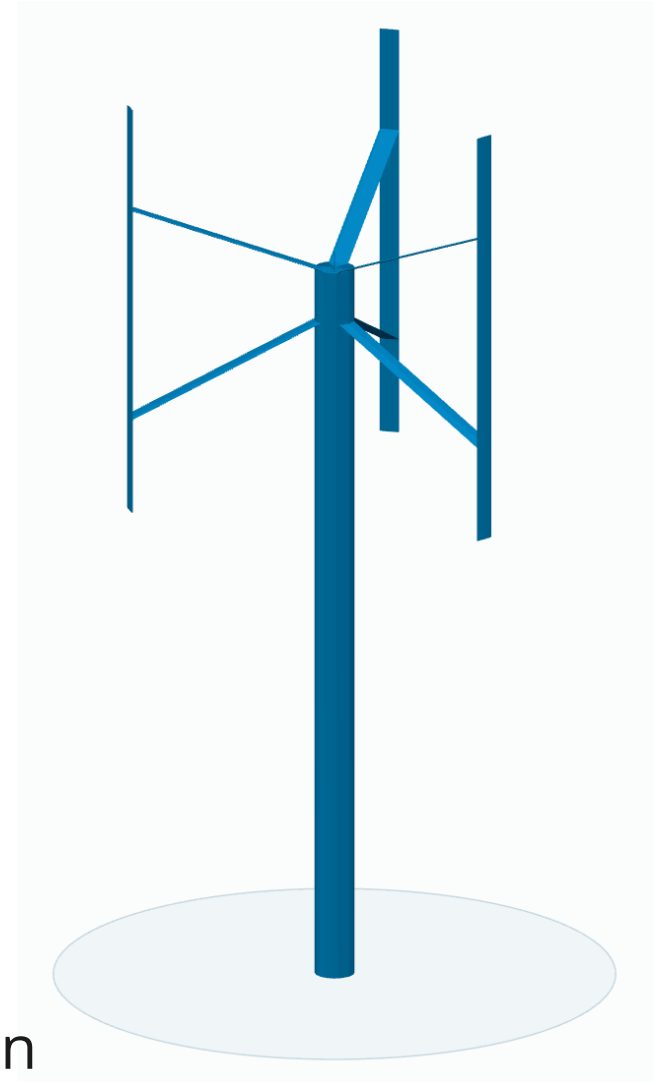
Ultimate stress

Longitudinal compression · 50 m/s

1.26×

Operating + Parked Miner's damage, 20 years

m = 10 sensitivity · 98% availability in 3–18 m/s
Rayleigh exposure includes extrapolation beyond 35 m/s



NEXT

Higher At-Risk Structure, ML + full case-specific validation

Questions?
Feedback?

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github.com/sandialabs/VorLap

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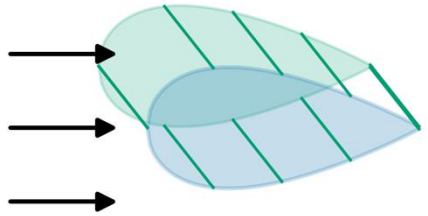
QBLADE: WELL DOCUMENTED AEROELASTIC SOLVER

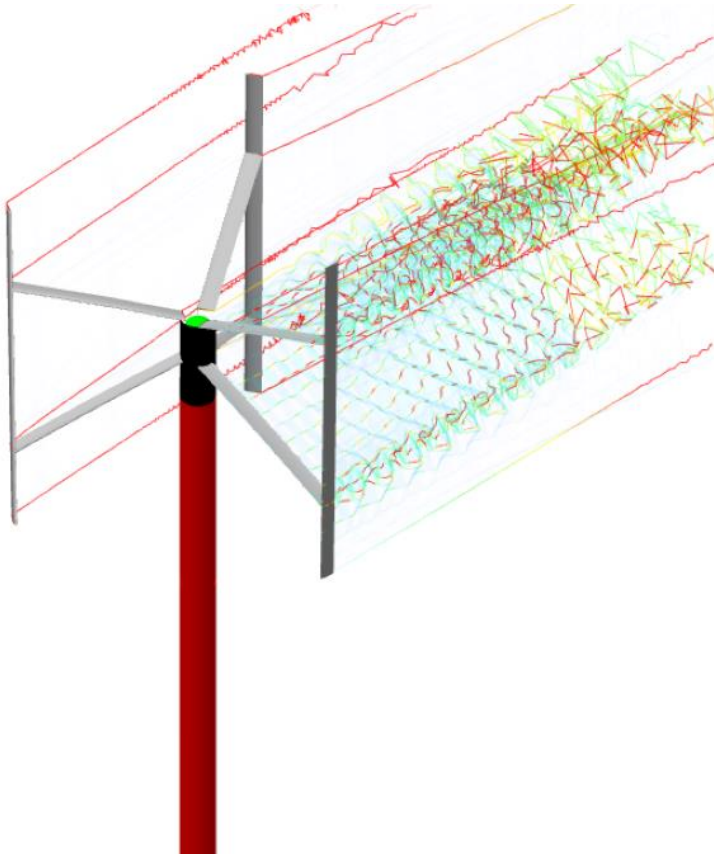


Turbulent Inflow

Airfoil Polars

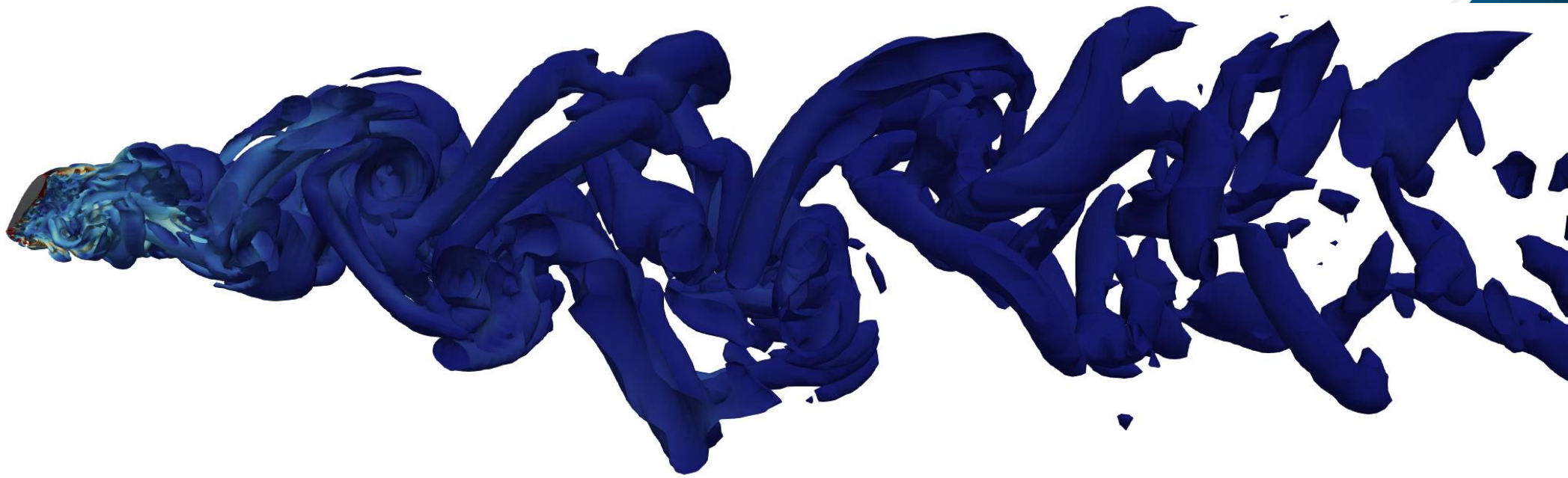
Blade and Wake Models

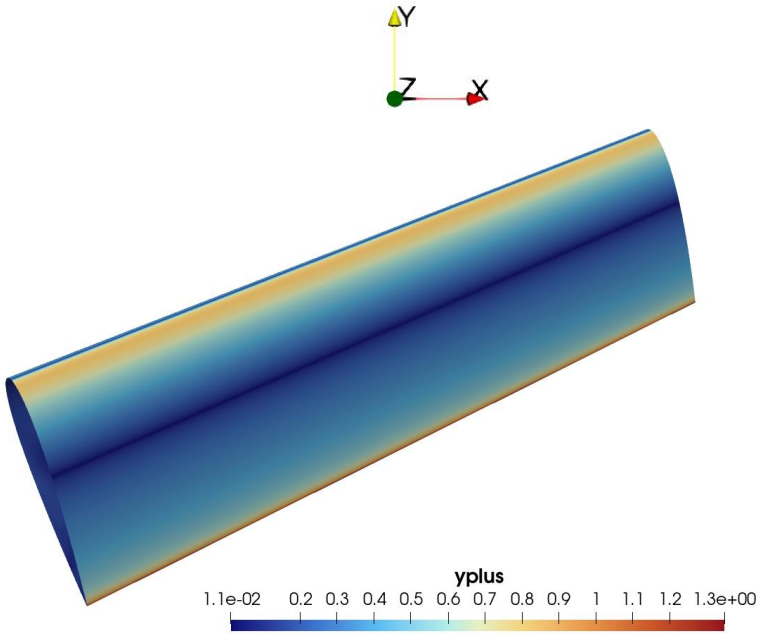
Structural Deflection

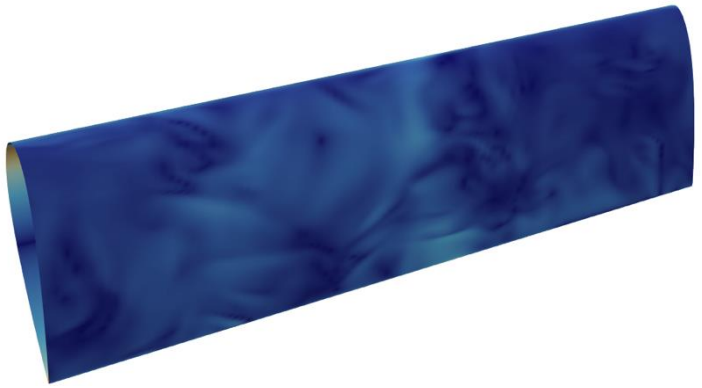




Contour Q-criterion of 1.0, Aoa=124 degrees





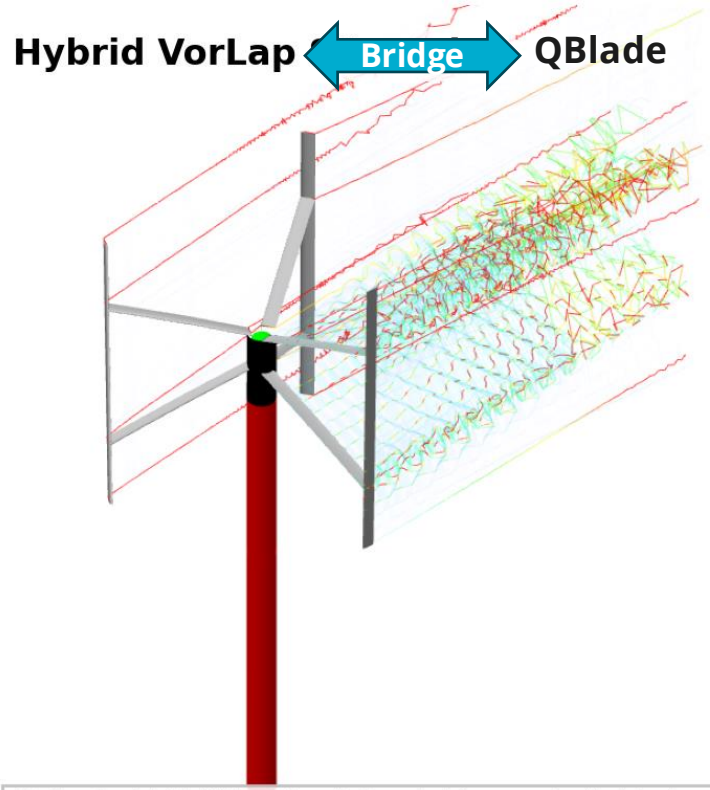


Y+ values over the airfoil at 84 degrees

Parked VIV Needs Engineering-level Loads Estimates

Shedding frequency
nears a natural frequency

Force and motion can
synchronize and reinforce

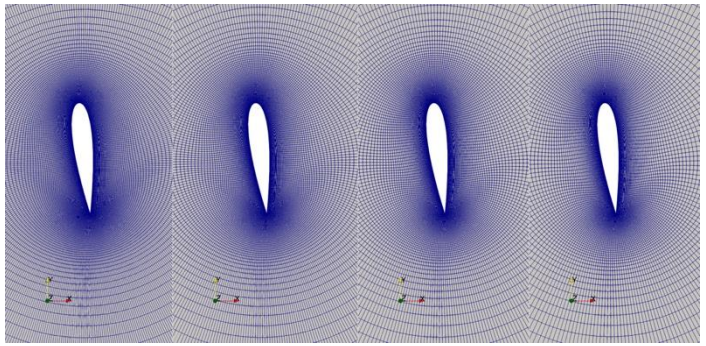


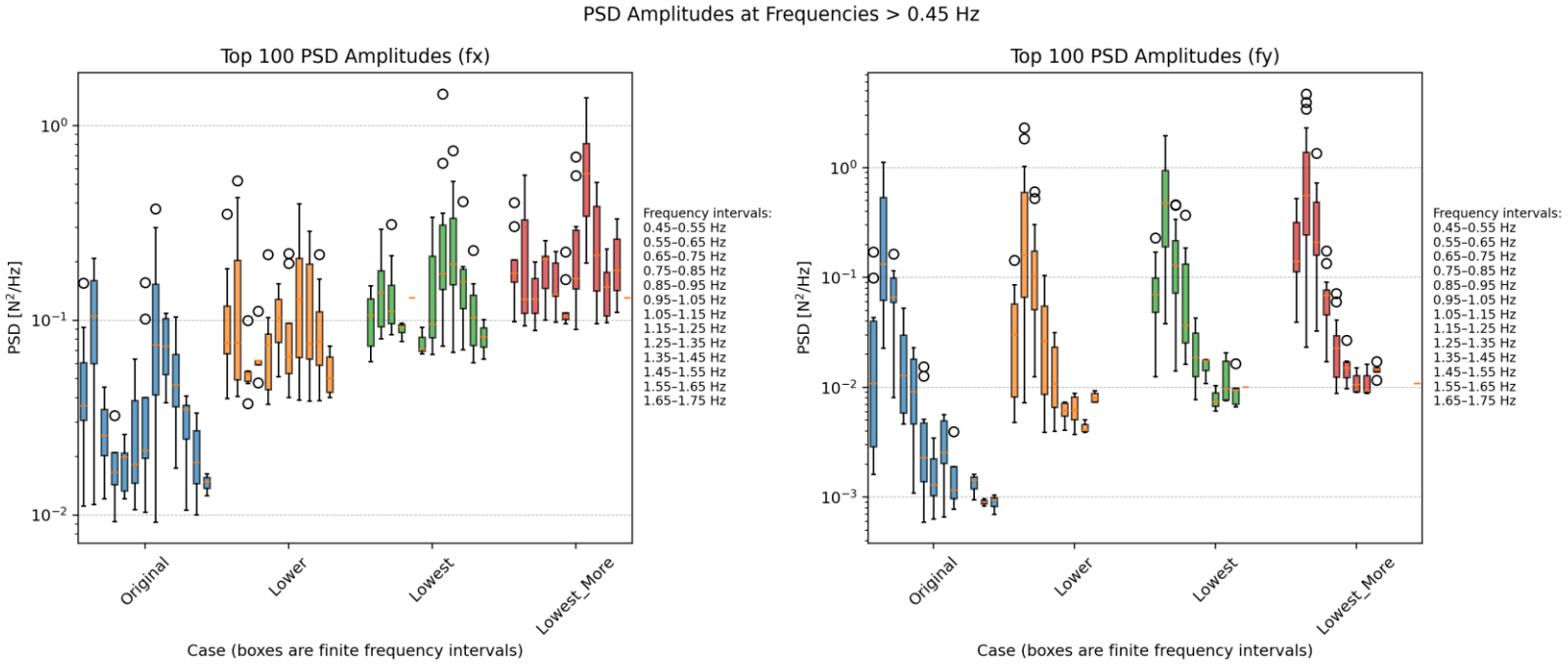
QBlade LLFVW wake (circulation color); VorLap forces active
U = 7.25 m s^{-1}; 1 RPM; t = 3.5250 s; negative-damping nodal force = 0.110 N

Identify the condition → estimate the load → prioritize detailed analysis

Mesh Study

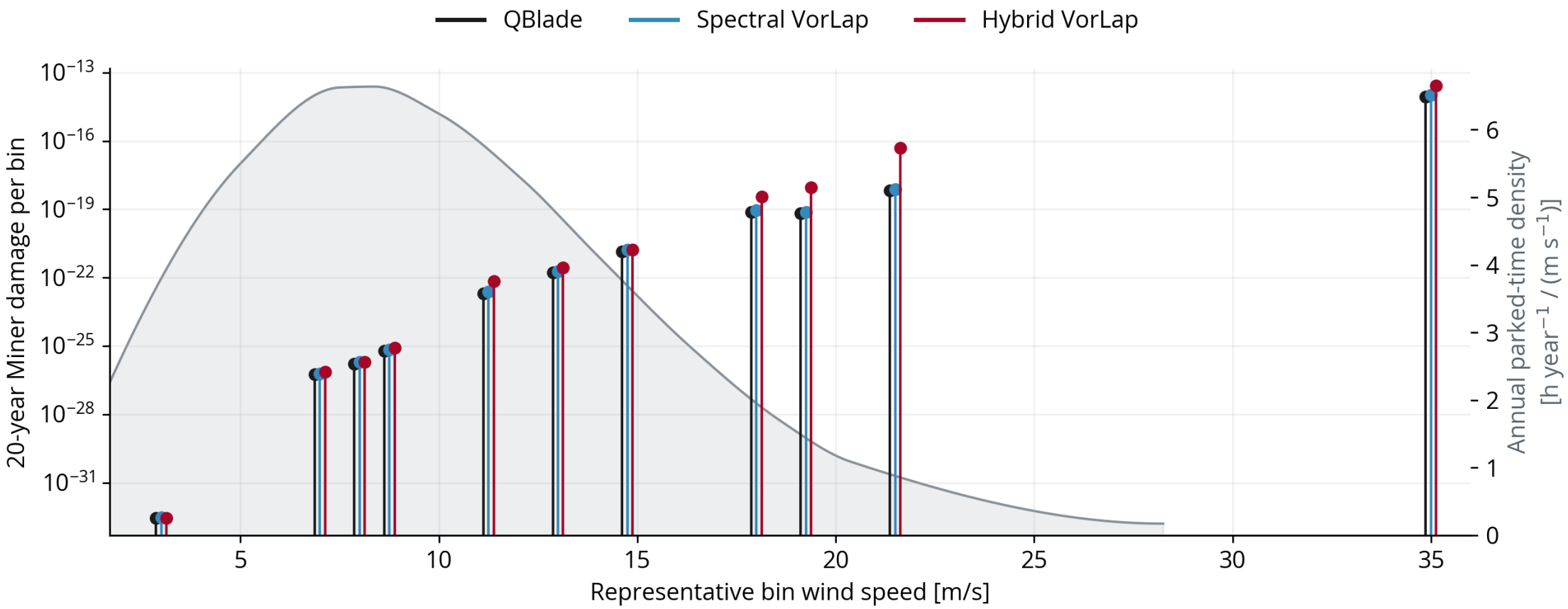
Case	Grid Size	Airfoil N	Max E	Span N	Y_{wall}
Lowest_More	4.4M	160	0.3 m	73	0.000041m
Lowest	6.8M	196	0.25 m	87	0.000041m
Lower	11.9M	256	0.185 m	101	0.000041m
Original	23.6M	335	0.125 m	121	0.000041m





The second and the eighth bar in each color cluster correspond to bin centers of 0.6Hz and 1.2Hz respectively. Fy binned accumulations show a clear peak at the 0.6Hz bin for all cases. In Fx, only the most-resolved and second-most-resolved cases show the 0.6Hz and 1.2Hz peaks. Choosing one of these meshes appears to be important for characterizing airfoil unsteadiness accurately.

20-Year Miner Damage: Common Material Model



QBlade 9.02×10^{-15} Spectral VorLap 1.03×10^{-14} Hybrid VorLap 2.62×10^{-14}

Hybrid / QBlade = 2.91 · common S–N + mean stress + y = 1.38 · 1% parked/year

Blade 1, 23% height, lower face (x/c = 0.30) · m = 10 continuation below 200 MPa

Numerical sensitivities remain material

Maximum-absolute moment changes at 35 m/s, relative to Hybrid VorLap

Seed / channel	Response off	Half timestep	33.33-Hz cap
4433458 / local Y	−0.37%	−1.83%	−4.78%
4433456 / local X	−1.54%	−0.18%	+5.05%

Nominal 66.67-Hz source cap lies at the timestep Nyquist frequency

These checks do not establish timestep convergence or isolate the response term

Backup: source and assessment boundaries

Section experiment → H-VAWT coefficients

Ehrmann (2014): NACA 0018 transverse response

High-fidelity blade response → geometry assessment

Horcas et al. (2020): four primitive families + withheld combined tip

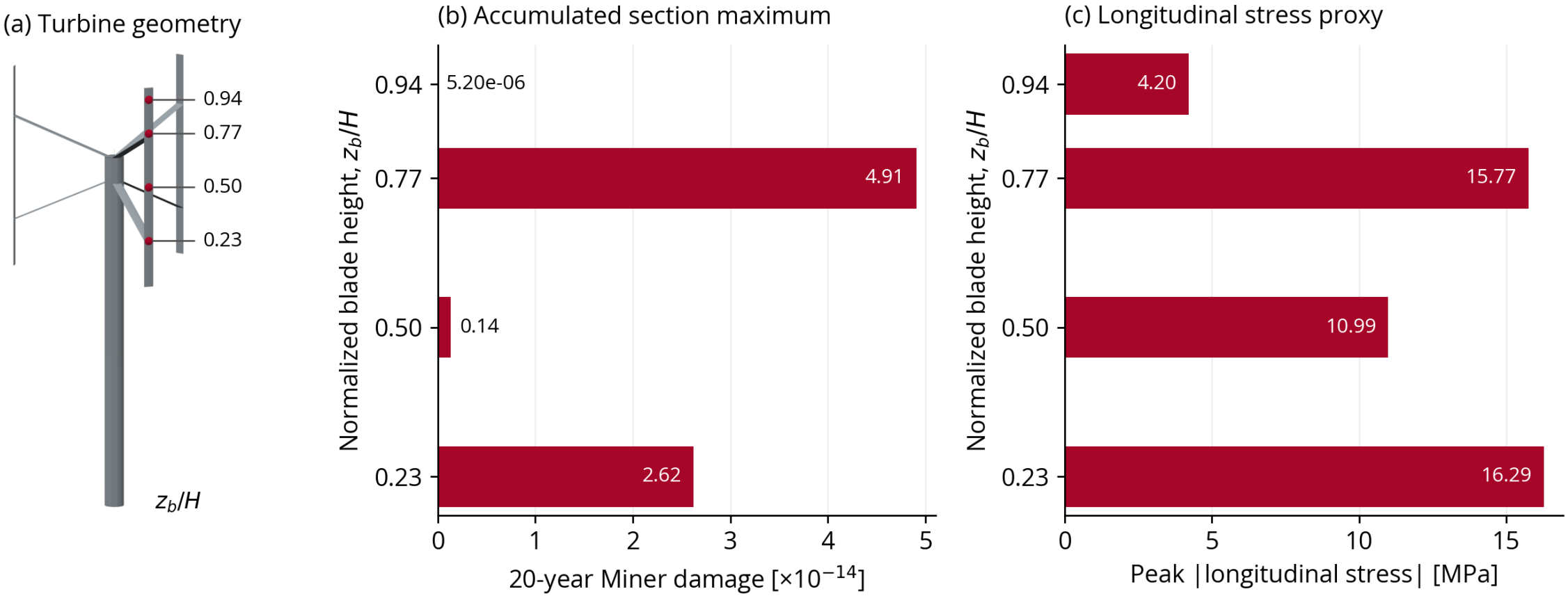
Blade simulation targets → complete-bridge reproduction

Grinderslev et al. (2022); Fu et al. (2026)

Current H-VAWT figures and values

Matched three-path records: 34 conditions, 102 simulations

Backup: Monitored Fatigue and Stress Hotspots

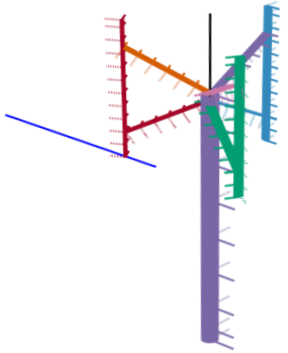


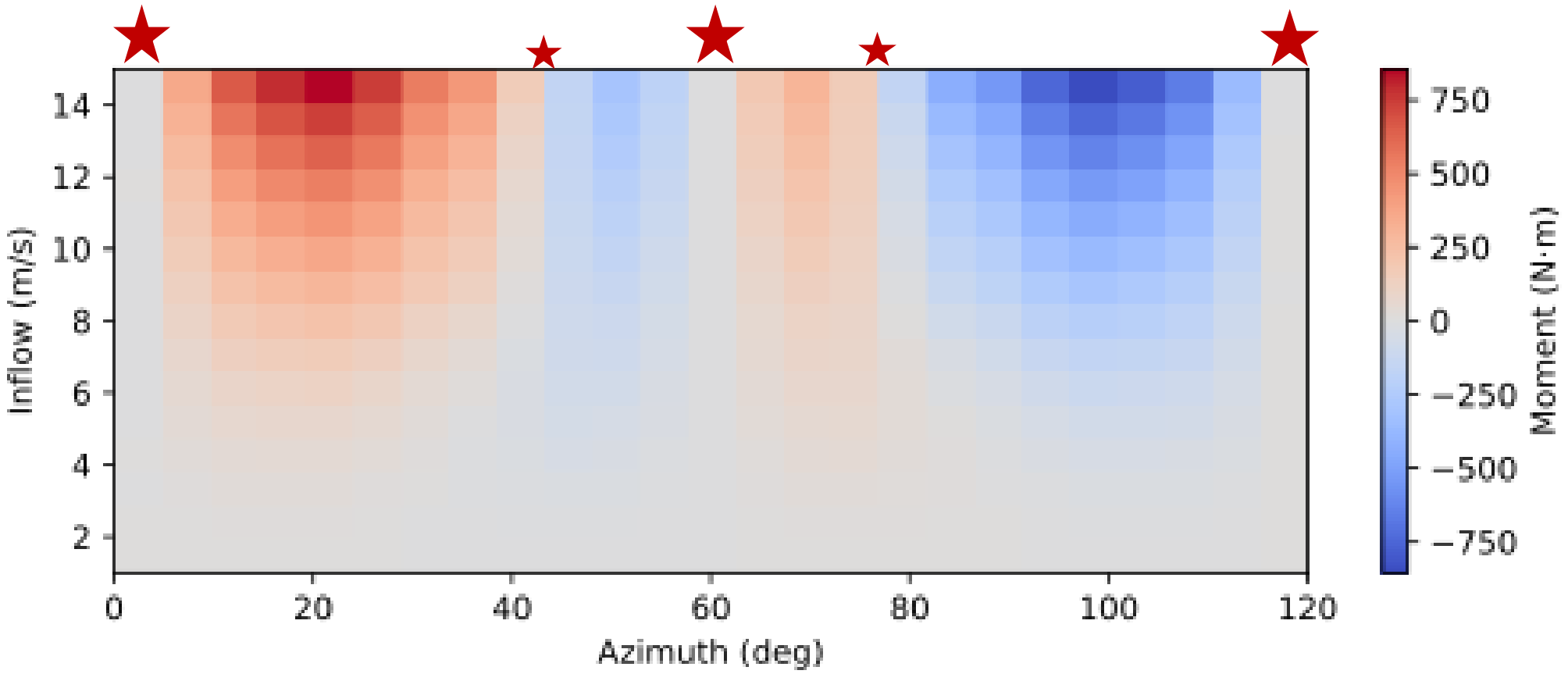
Highest monitored damage: 77% height · near the upper strut

Peak longitudinal stress: 23% height · fatigue reflects cycle amplitudes and exposure

Four monitored Blade 1 stations; full-turbine fatigue coverage requires additional structural histories

DEMO: PARKING POSITIONS







*Any azimuth can be analyzed

Backup: Equations and Symbol Definitions

Indices: i = blade section; k = frequency harmonic; m = structural mode; j = fatigue-cycle bin.
L = lift; D = drag; $f_{n,m}$ = natural frequency of mode m; spec = spectral; a = apparent in U_a; $|\cdot|$ = magnitude.

Spectral scaling · slide 5

$$f = \mathrm{St}\, U_a / D_{St} \qquad |\hat{F}| = \tfrac{1}{2}\rho U_a^2 c \Delta s\, |\hat{C}|$$

$$D_{St} = c \max(|\sin\alpha|, t/c)$$

$$\text{Full lift-spectrum RSS} = [\textstyle\sum_{k>0} |\hat{C}_{L,k}|^2]^{1/2}$$

f: frequency [Hz]; St: Strouhal number; U_a: apparent speed [m/s].
D_{St}: projected-chord scale; c: chord; t: thickness; Δs: span [m].
ρ: air density [kg/m³]; α: angle of attack; $\hat{F}$: force harmonic [N].
$\hat{C}$: dimensionless force coefficient; hat: Fourier; RSS: root-sum-square.

Captured lift → modal damping · slide 6

$$C_{spec,i,m} = [\textstyle\sum_k \eta_{i,k,m}\, |\hat{C}_{L,i,k}|^2]^{1/2}$$

$$B_{spec,m} = \textstyle\sum_i \tfrac{1}{2}\rho U_{a,i} c_i \Delta s_i\, C_{spec,i,m}\, \gamma_{i,m} p_{i,m}^2$$

η: fraction of squared harmonic amplitude assigned to a mode.
C_{spec}: dimensionless captured lift coefficient (harmonic RSS).
B_{spec}: modal damping basis [N·s/m].
p: local mode-shape magnitude; γ: lift–motion alignment.
$p = \|\varphi\|$; $\gamma = |\hat{e}_L \cdot \varphi / p|$ ($\gamma = 0$ where $p = 0$).
φ: dimensionless modal displacement vector; $\hat{e}_L$: lift unit vector.
Sum over k collects harmonics; sum over i assembles sections.

Motion-correlated force · slide 7

$$Q_m = H\, B_{spec,m} [1 - (\hat{A}_m / (\Lambda L_{ref,m}))^2]\, \dot{q}_{f,m}$$

Q_m: generalized modal force [N].
H: calibrated dimensionless gain; Λ: limiting-amplitude ratio.
$\hat{A}_m$: live peak-amplitude estimate [m]; $L_{ref,m}$: reference length [m].
$\dot{q}_{f,m}$: filtered modal velocity [m/s]; subscript f means filtered.
$HB_{spec,m}$: zero-amplitude feedback coefficient [N·s/m].
The bracket is zero at $\hat{A}_m = \Lambda L_{ref,m}$.

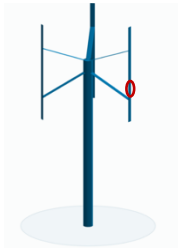
Fatigue, equivalent load and strength · slides 14, 20

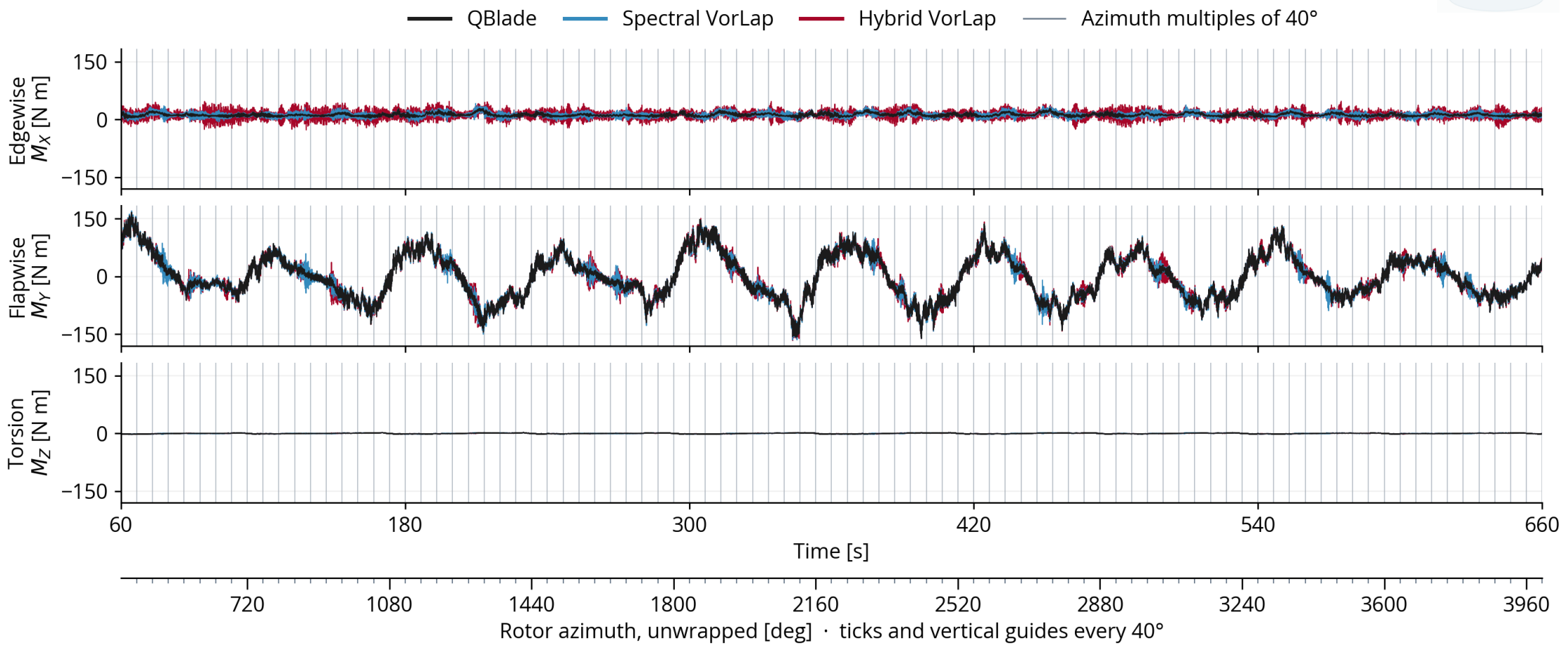
$$D = \textstyle\sum_j n_j / N_f(a_j) = N_{eq} / N_f(\Delta\sigma_{DEL}/2)$$

$$S_L = \min(X_t/\sigma_{t,max},\, X_c/|\sigma_{c,min}|)$$

D: Miner damage; n_j: counted cycles; a_j: stress amplitude.
$N_f(a)$: cycles to failure at amplitude a; subscript f means failure.
N_{eq}: reference cycles; $\Delta\sigma_{DEL}$: equivalent stress range [MPa].
DEL: damage-equivalent load; S–N: stress amplitude–cycle curve.
m = 14.46 on the S–N slide is a slope exponent, not a mode.
S_L: longitudinal safety factor; X_t, X_c: tensile/compressive strengths.
$\sigma_{t,max}$, $\sigma_{c,min}$: extreme tensile/compressive longitudinal stresses.
Strengths and stresses use the same units; D and S_L are unitless.

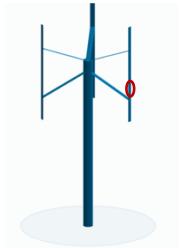
7 m/s — 40° Azimuth Guides

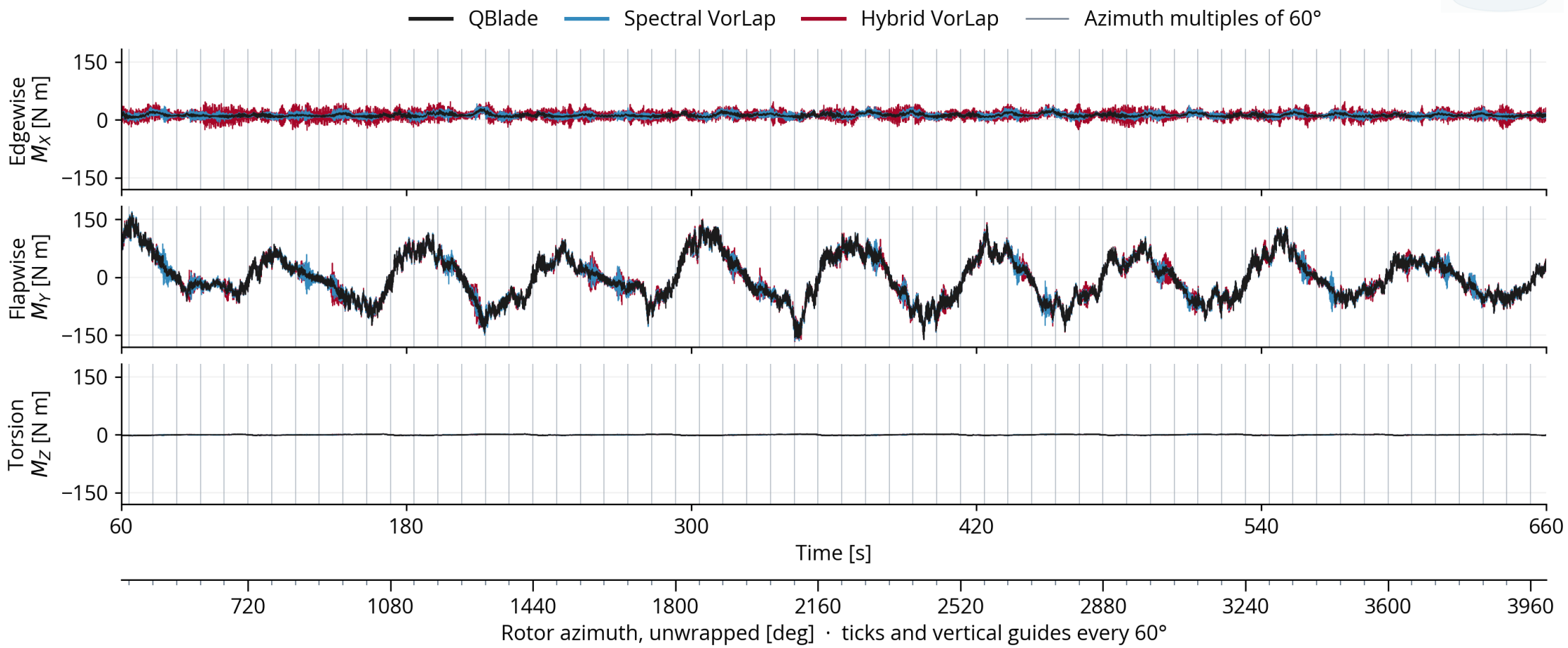




Alternative to slide 15 · 7 m/s · Blade 1, 23% height · seed 4433456 · 60–660 s
40° orientation guides · Prescribed 1 rpm; these are not predicted settling positions.

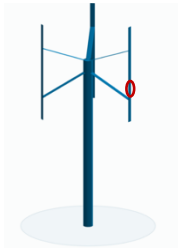
7 m/s — 60° Azimuth Guides

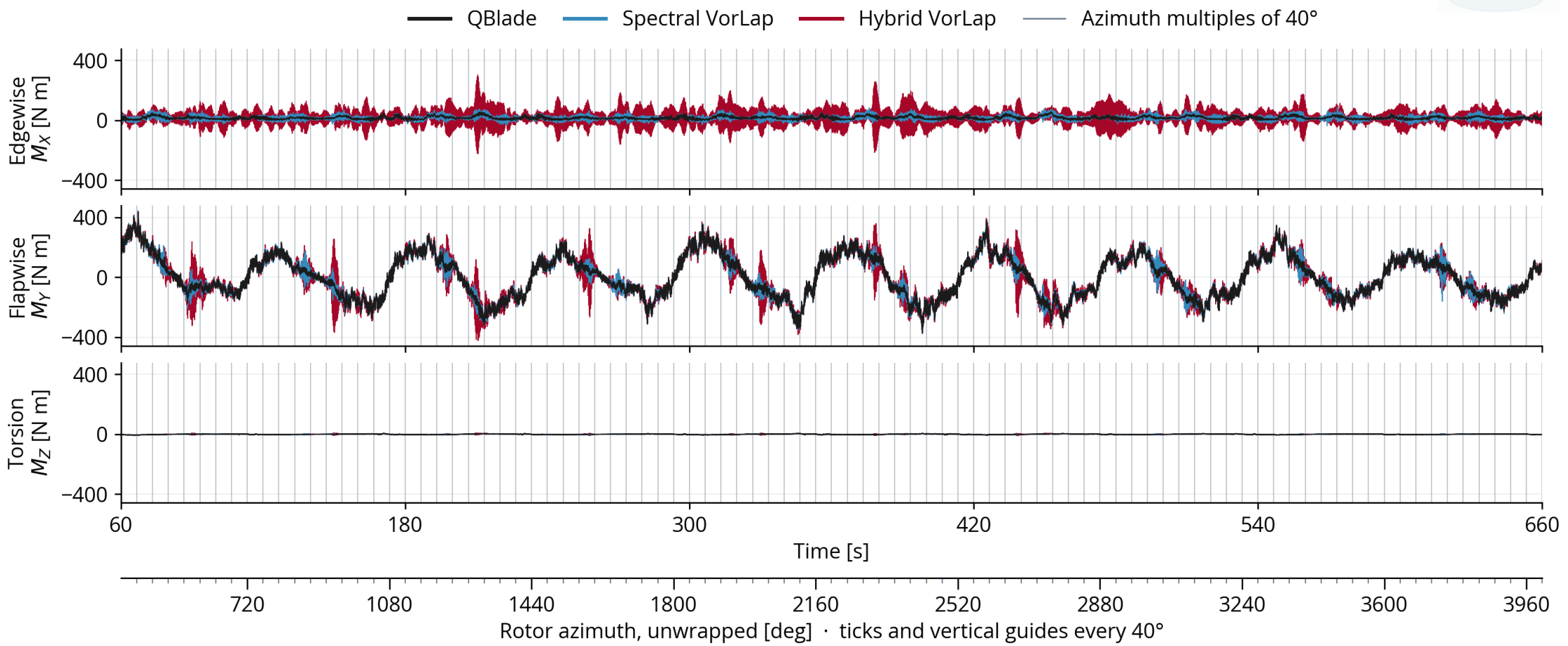




Alternative to slide 15 · 7 m/s · Blade 1, 23% height · seed 4433456 · 60–660 s
60° orientation guides · Prescribed 1 rpm; these are not predicted settling positions.

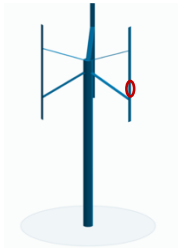
11.25 m/s — 40° Azimuth Guides

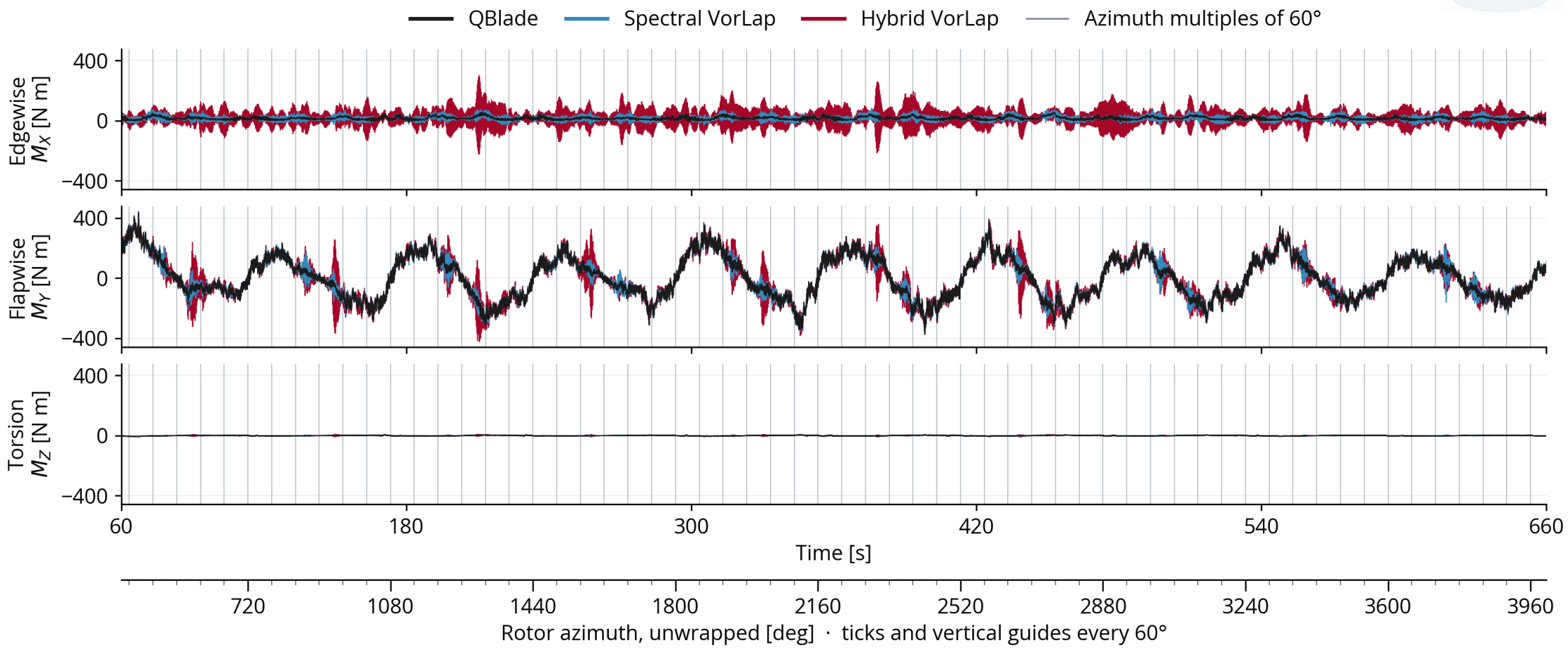




Alternative to slide 16 · 11.25 m/s · Blade 1, 23% height · seed 4433456 · 60–660 s
40° orientation guides · Prescribed 1 rpm; these are not predicted settling positions.

11.25 m/s — 60° Azimuth Guides





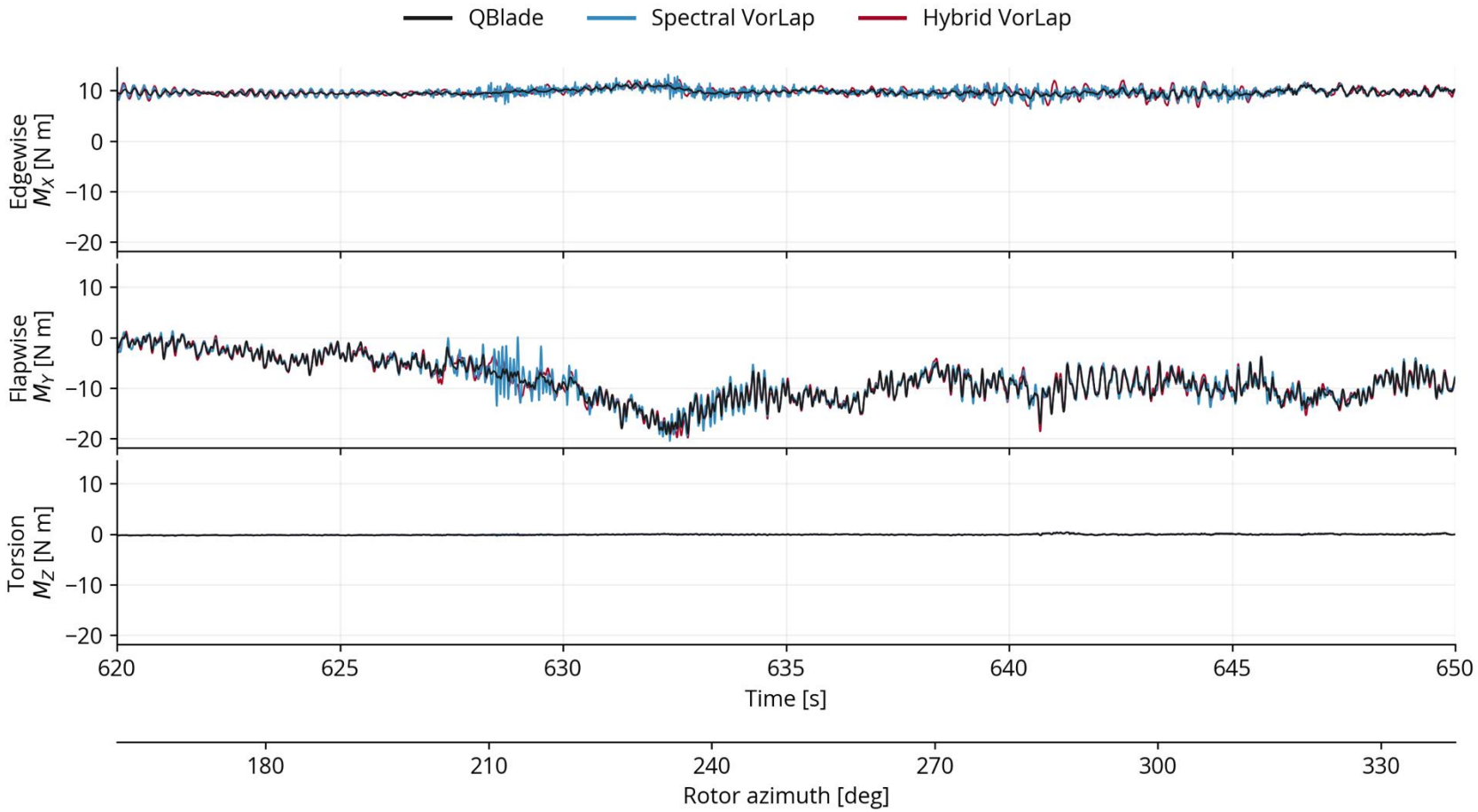
Alternative to slide 16 · 11.25 m/s · Blade 1, 23% height · seed 4433456 · 60–660 s
60° orientation guides · Prescribed 1 rpm; these are not predicted settling positions.

Backup: 3 m/s — Moments on a Common Scale

Edge

Flap

Torsion



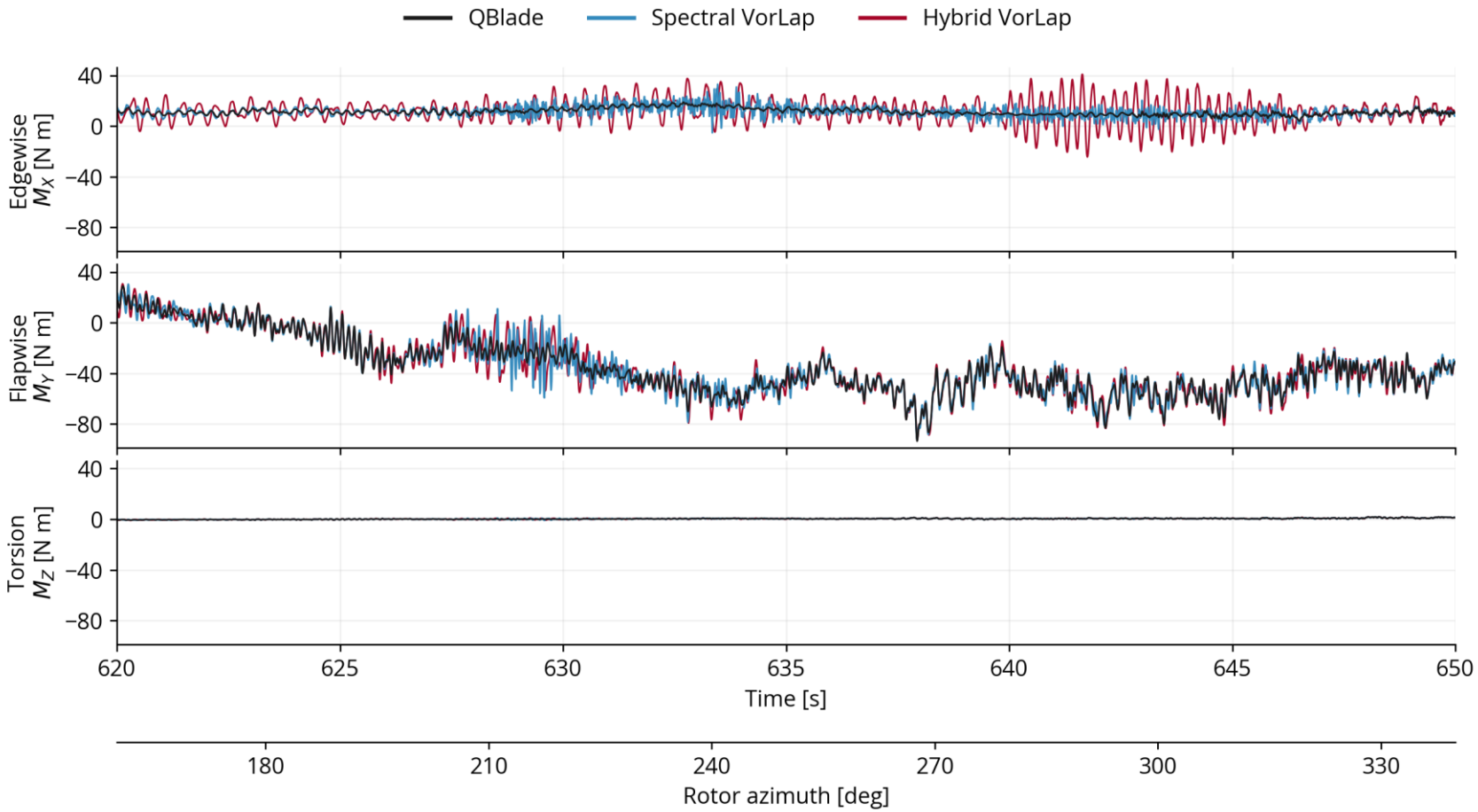
3 m/s · Blade 1, 23% height · seed 4433456 · 620–650 s

Backup: 7 m/s — Moments on a Common Scale

Edge

Flap

Torsion



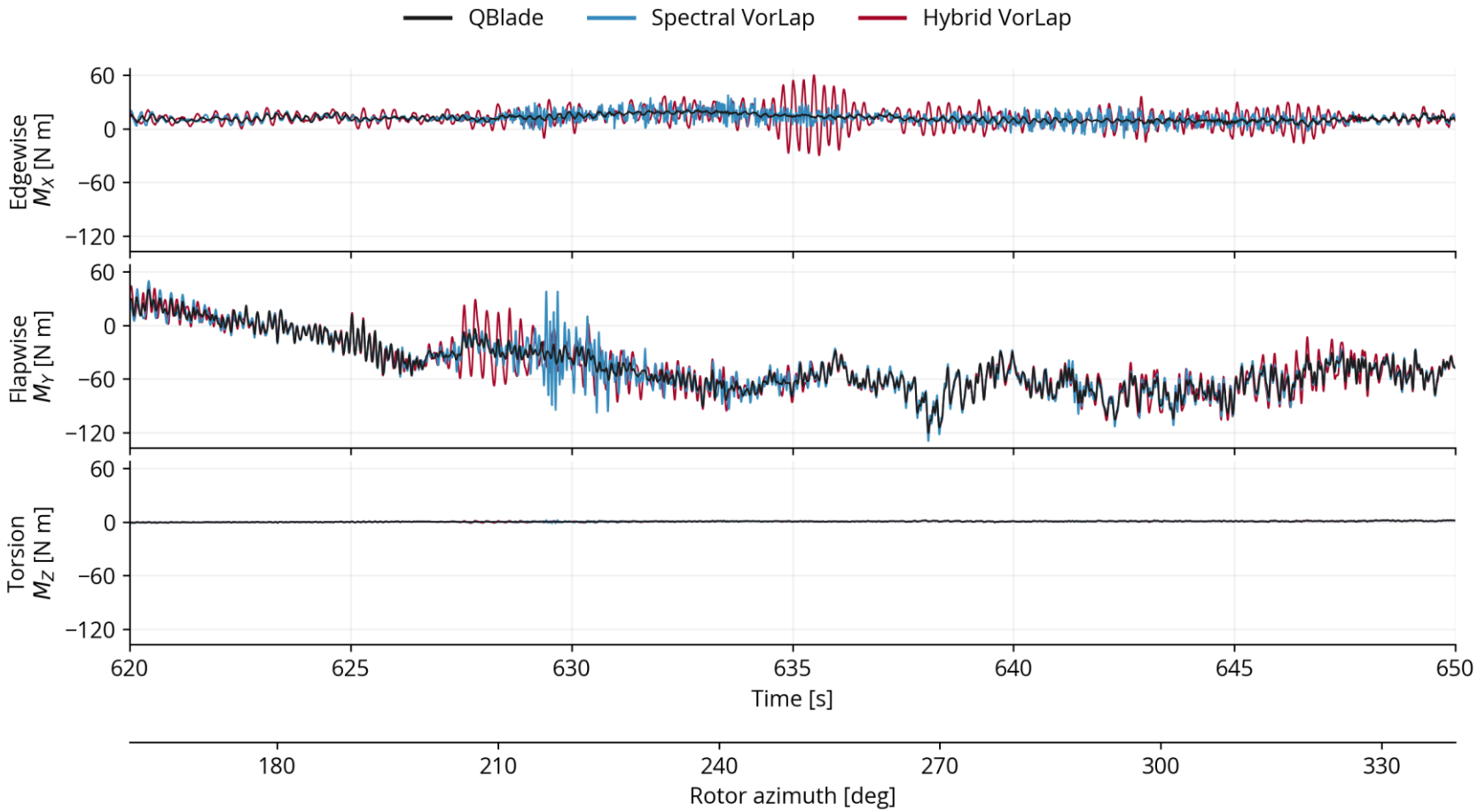
7 m/s · Blade 1, 23% height · seed 4433456 · 620–650 s

Backup: 8 m/s — Moments on a Common Scale

Edge

Flap

Torsion



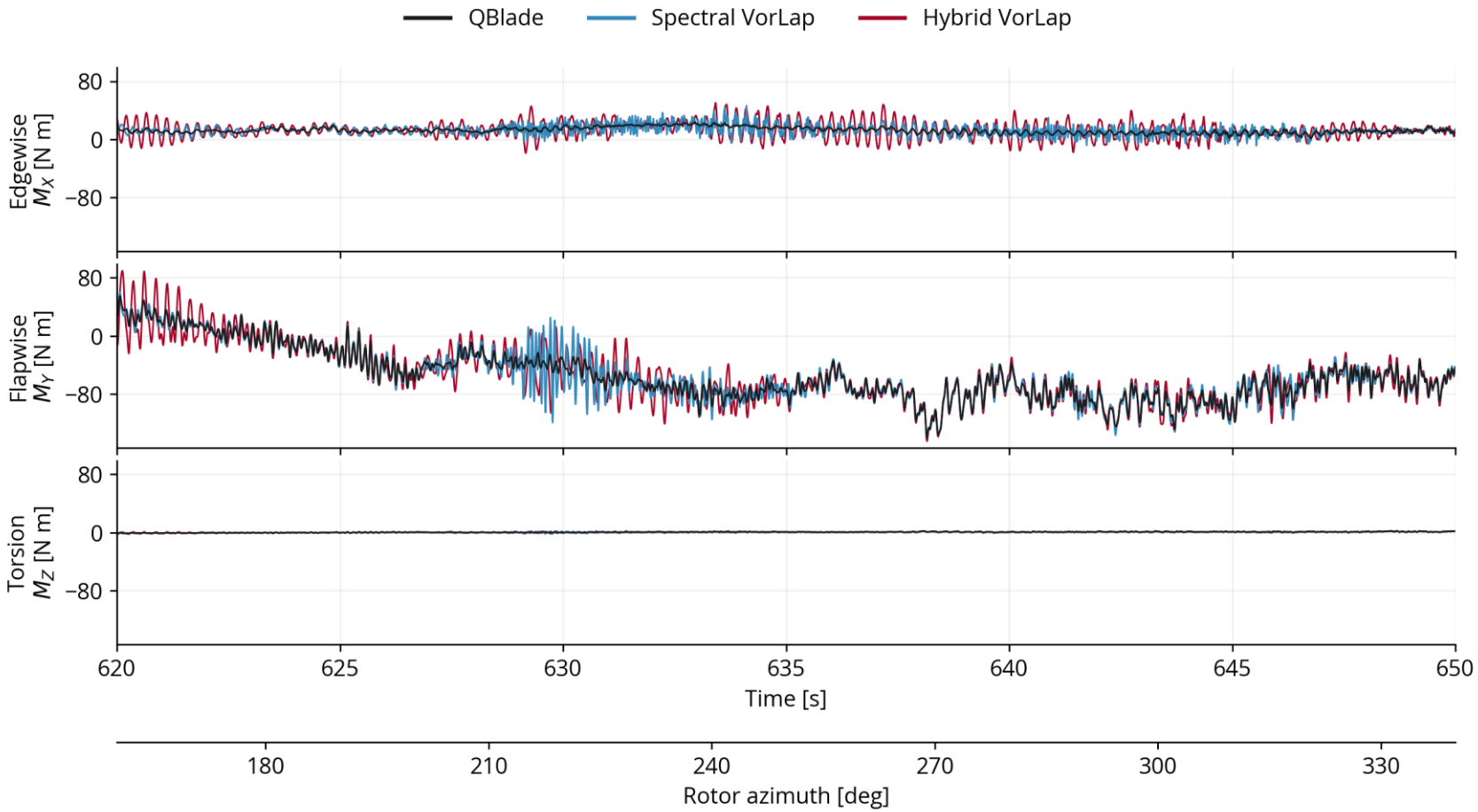
8 m/s · Blade 1, 23% height · seed 4433456 · 620–650 s

Backup: 8.75 m/s — Moments on a Common Scale

Edge

Flap

Torsion



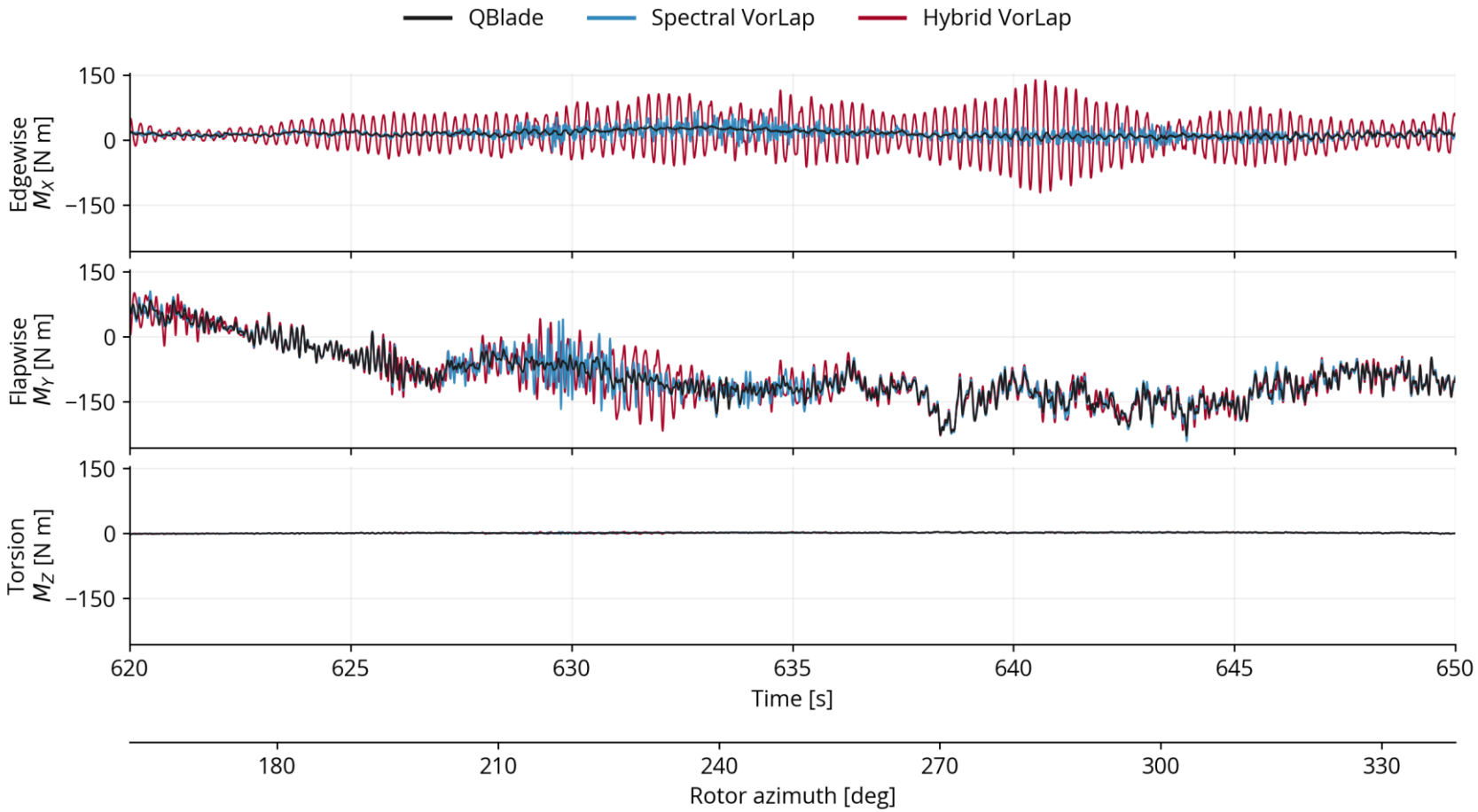
8.75 m/s · Blade 1, 23% height · seed 4433456 · 620–650 s

Backup: 11.25 m/s — Moments on a Common Scale

Edge

Flap

Torsion



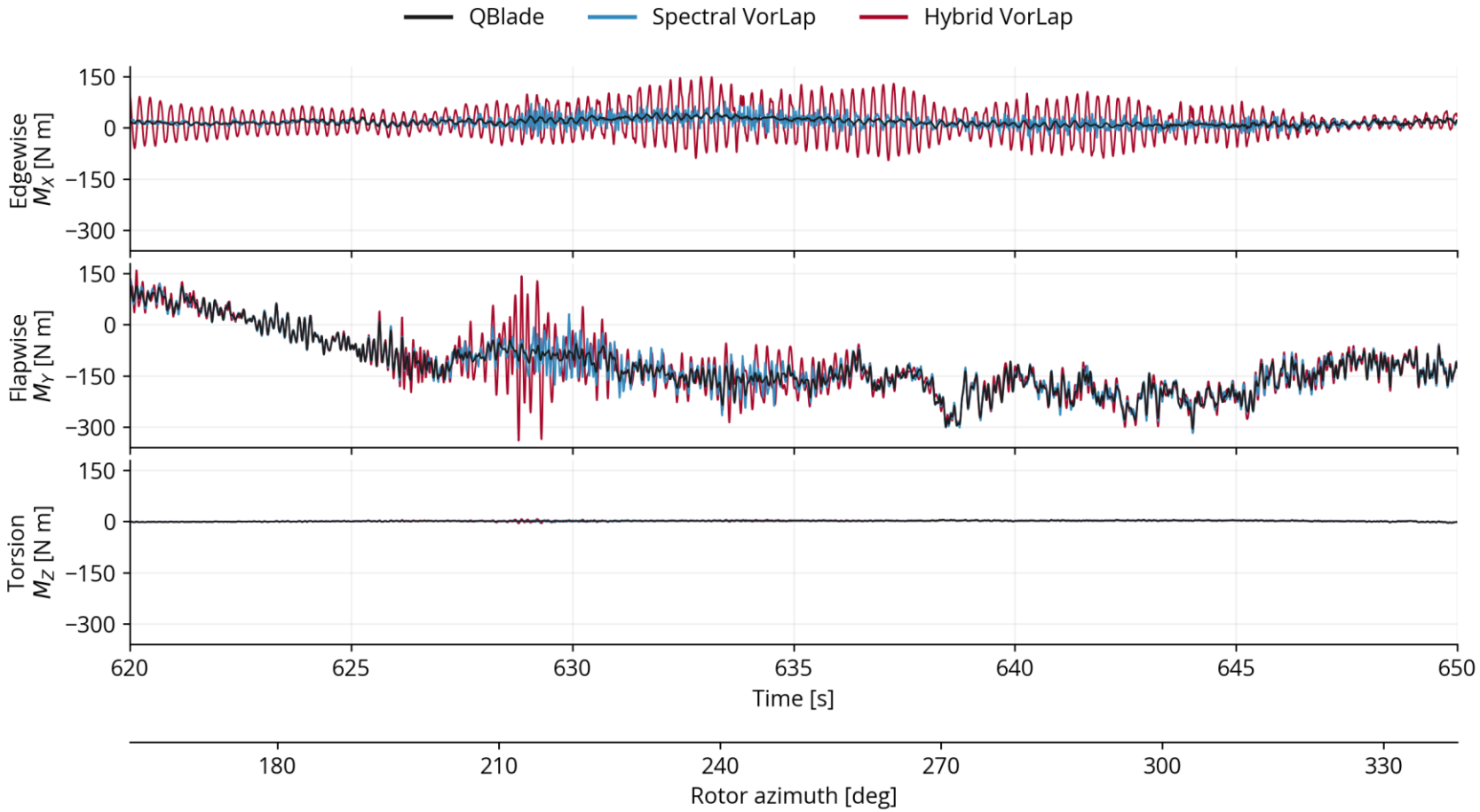
11.25 m/s · Blade 1, 23% height · seed 4433456 · 620–650 s

Backup: 13 m/s — Moments on a Common Scale

Edge

Flap

Torsion



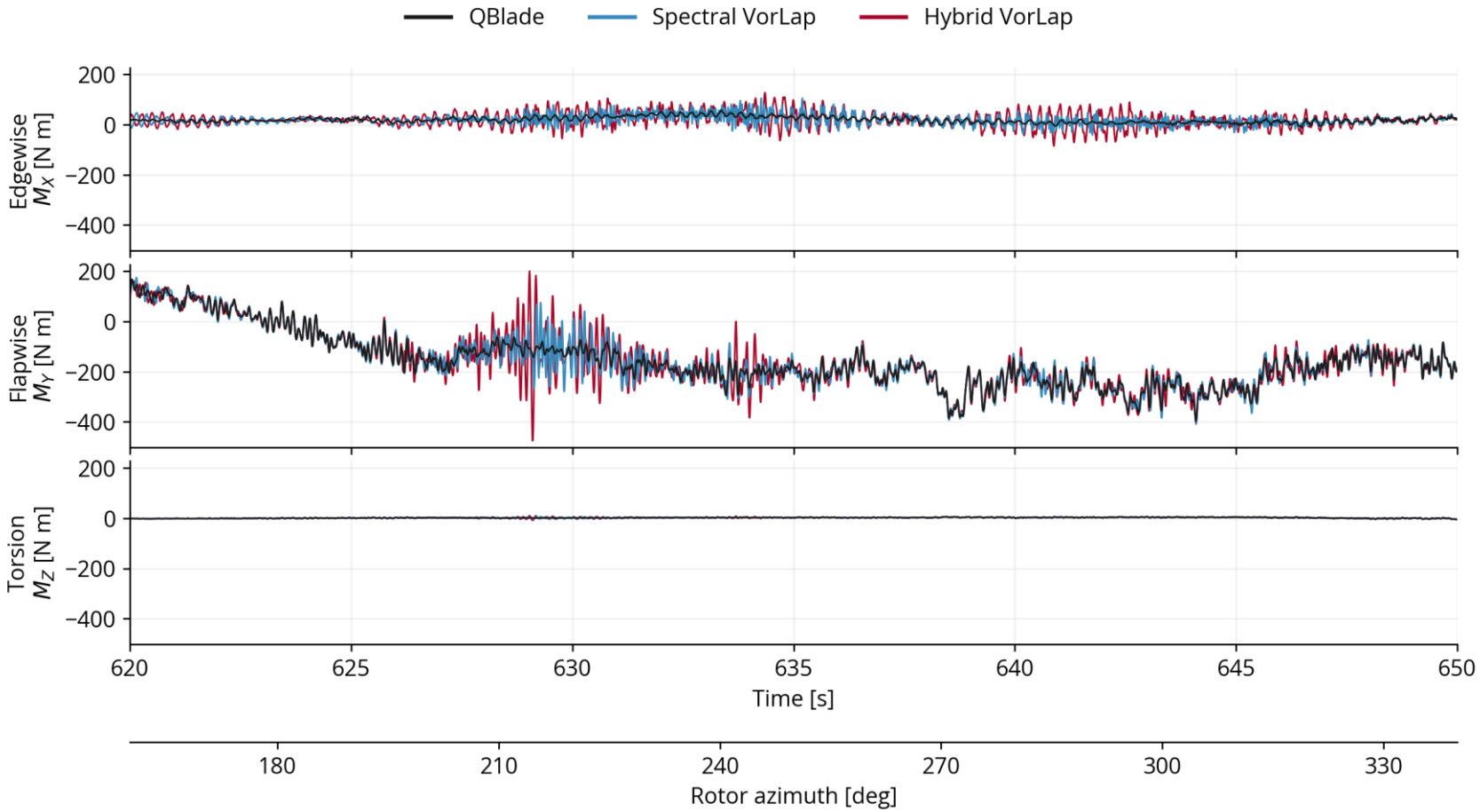
13 m/s · Blade 1, 23% height · seed 4433456 · 620–650 s

Backup: 14.75 m/s — Moments on a Common Scale

Edge

Flap

Torsion



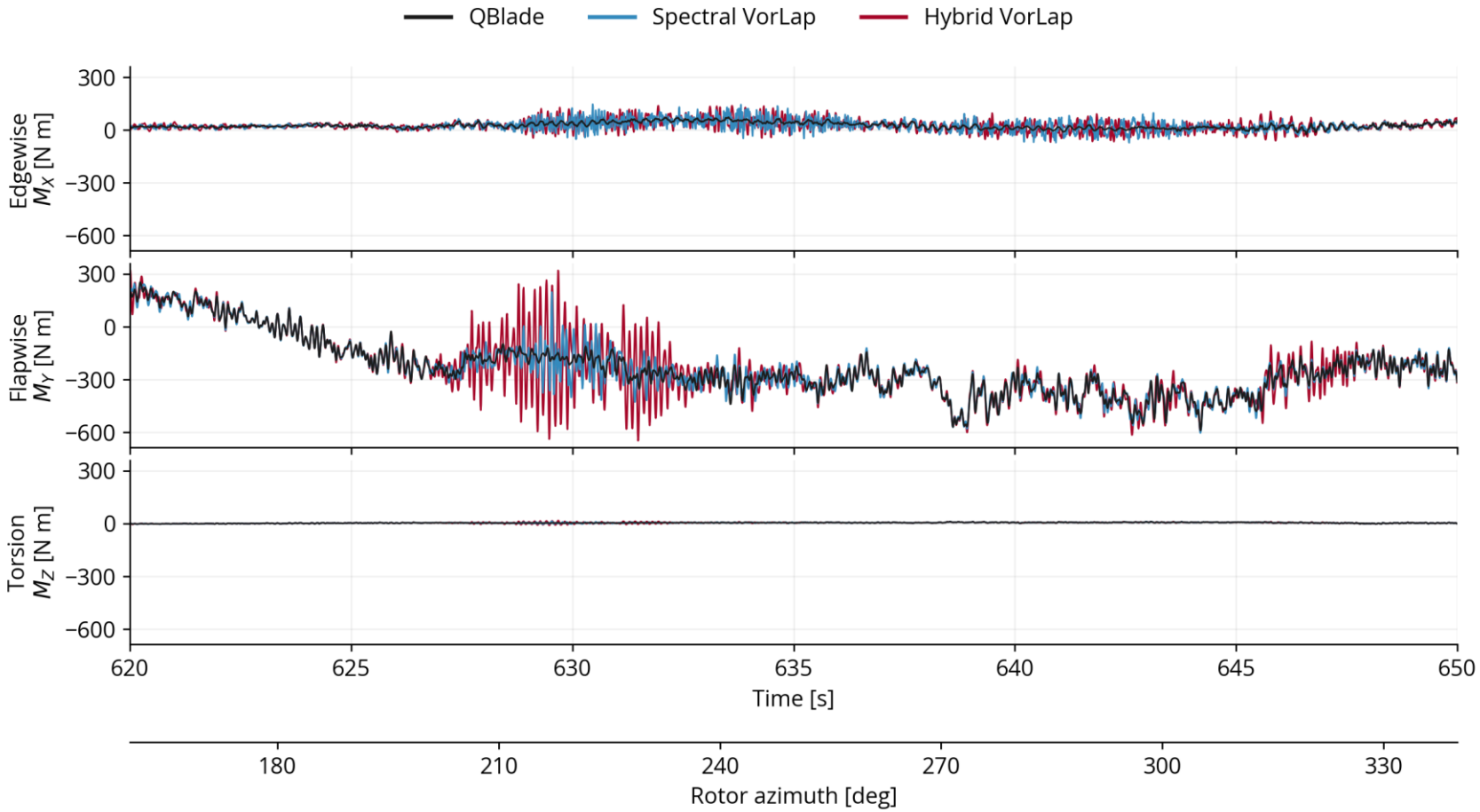
14.75 m/s · Blade 1, 23% height · seed 4433456 · 620–650 s

Backup: 18 m/s — Moments on a Common Scale

Edge

Flap

Torsion



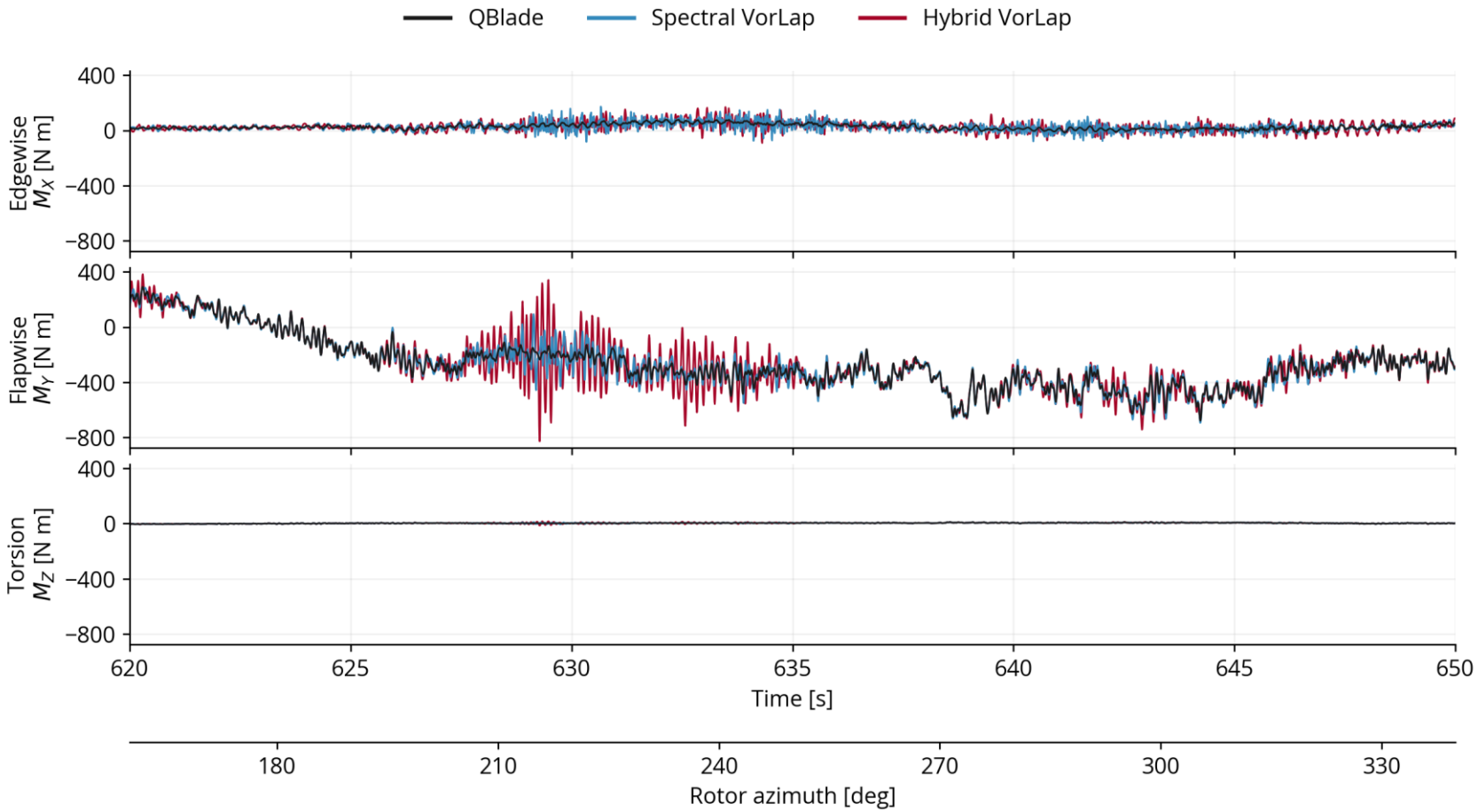
18 m/s · Blade 1, 23% height · seed 4433456 · 620–650 s

Backup: 19.25 m/s — Moments on a Common Scale

Edge

Flap

Torsion



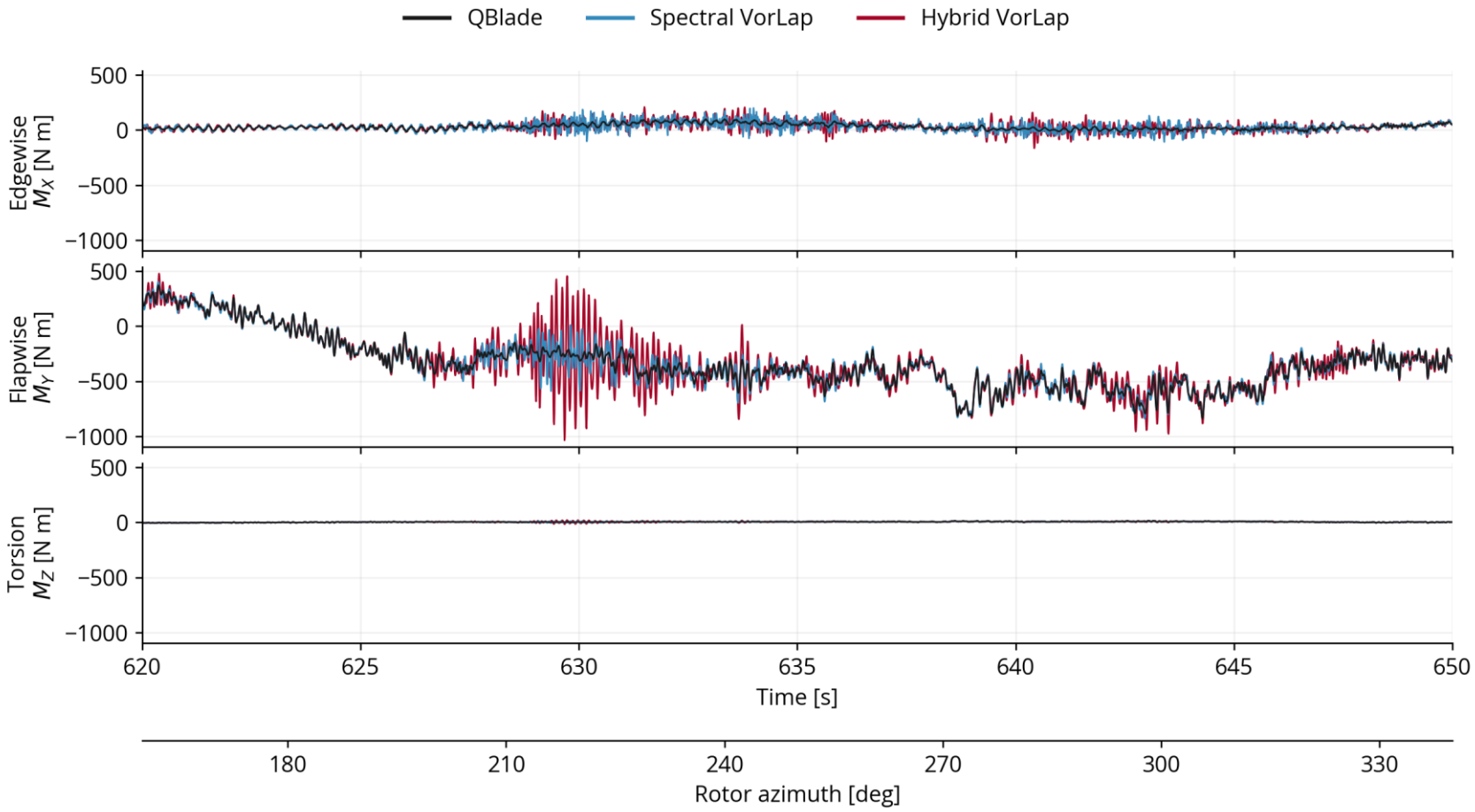
19.25 m/s · Blade 1, 23% height · seed 4433456 · 620–650 s

Backup: 21.5 m/s — Moments on a Common Scale

Edge

Flap

Torsion



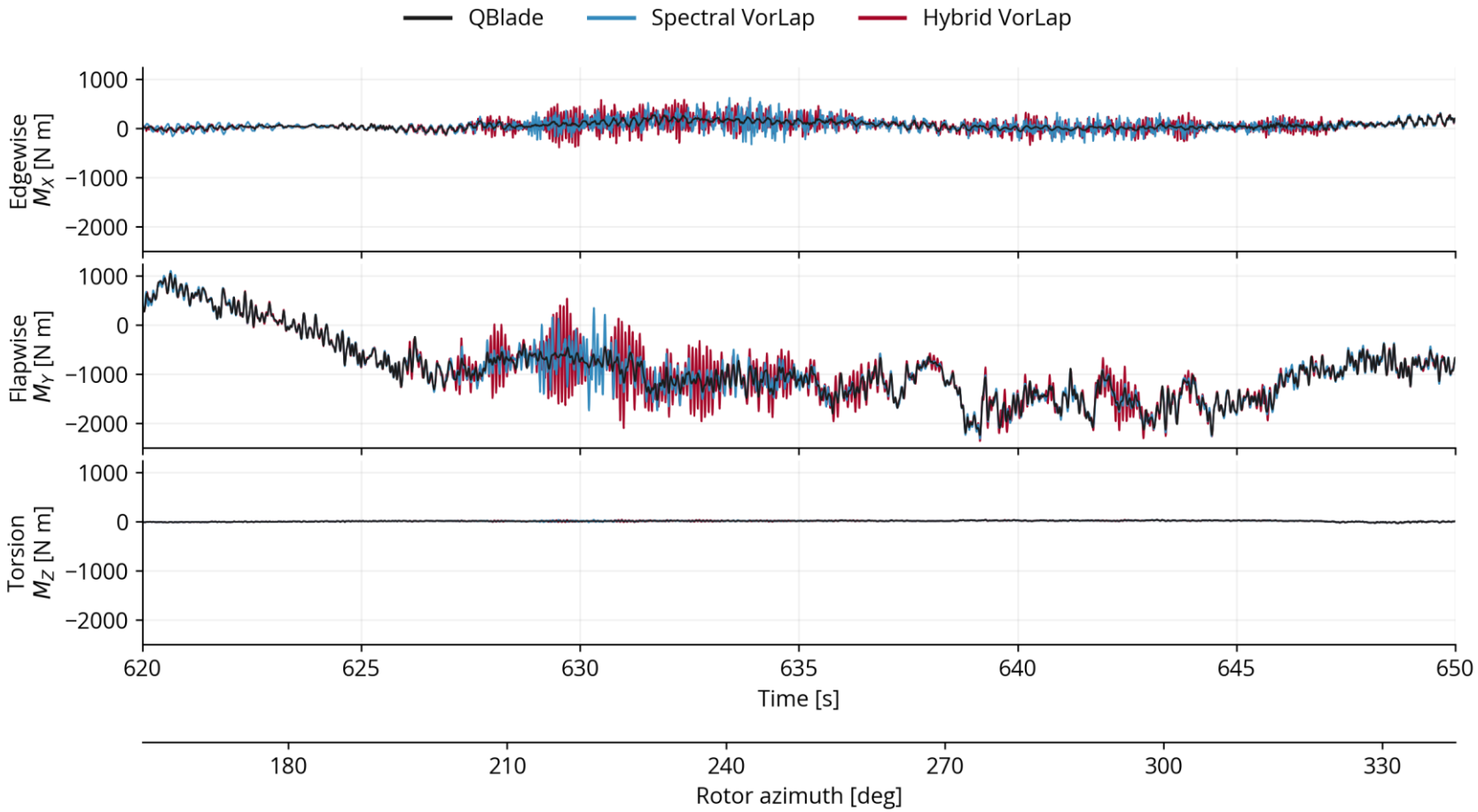
21.5 m/s · Blade 1, 23% height · seed 4433456 · 620–650 s

Backup: 35 m/s — Moments on a Common Scale

Edge

Flap

Torsion



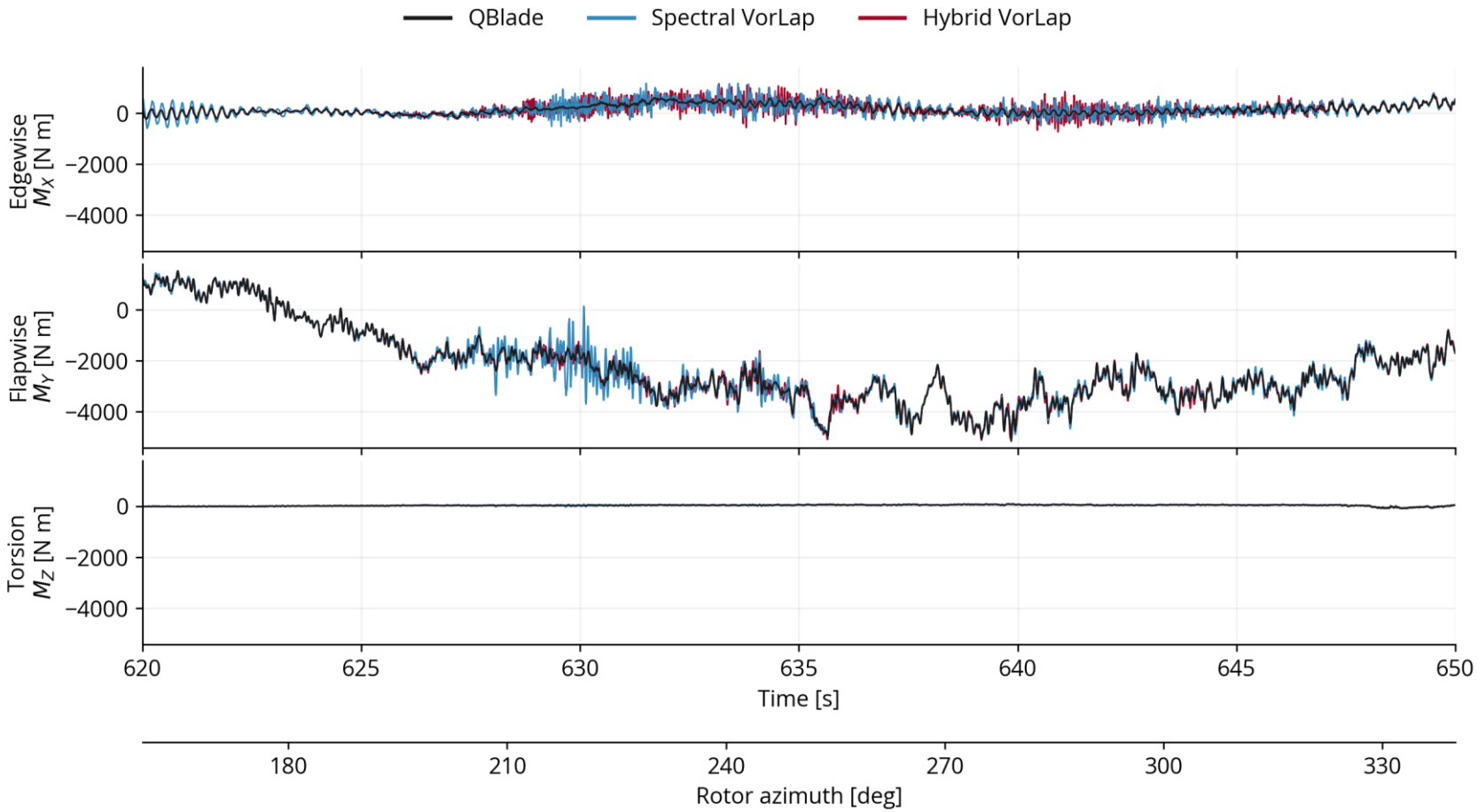
35 m/s · Blade 1, 23% height · seed 4433456 · 620–650 s

Backup: 50 m/s — Moments on a Common Scale

Edge

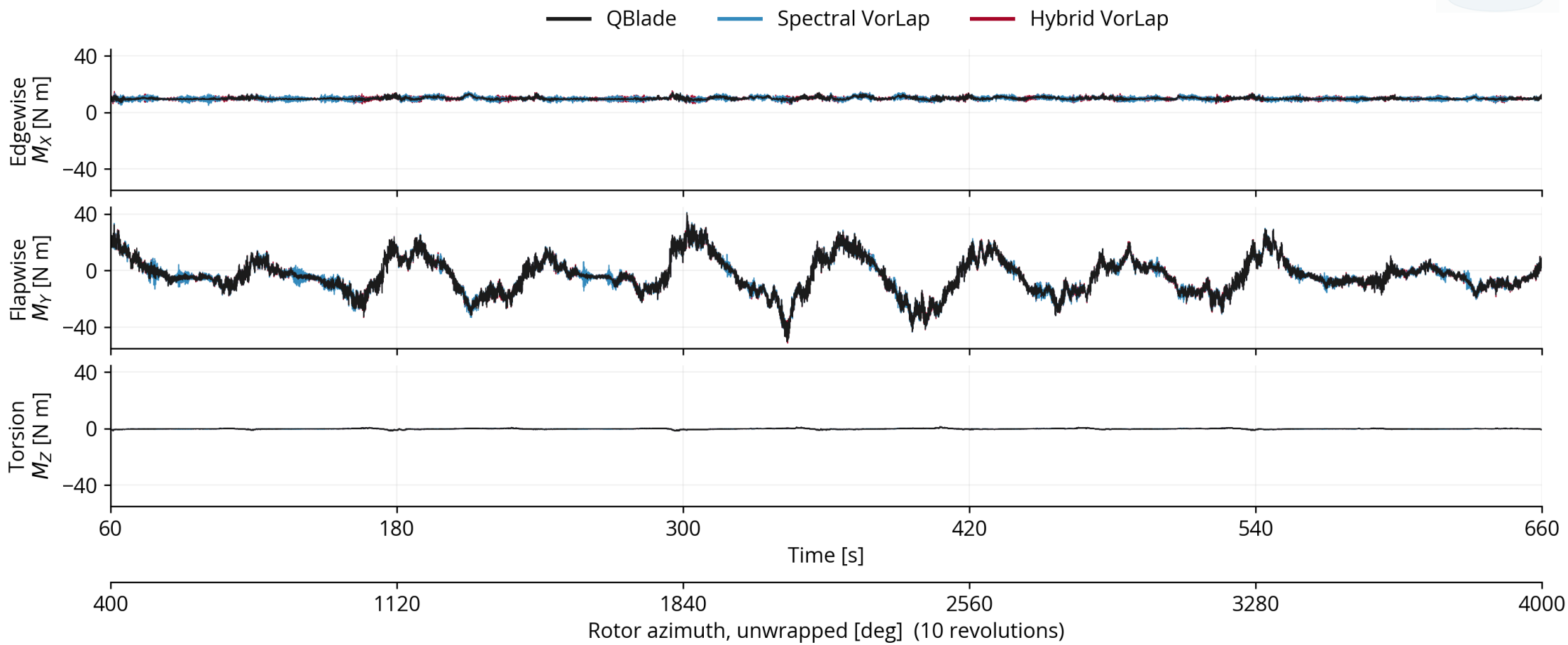
Flap

Torsion



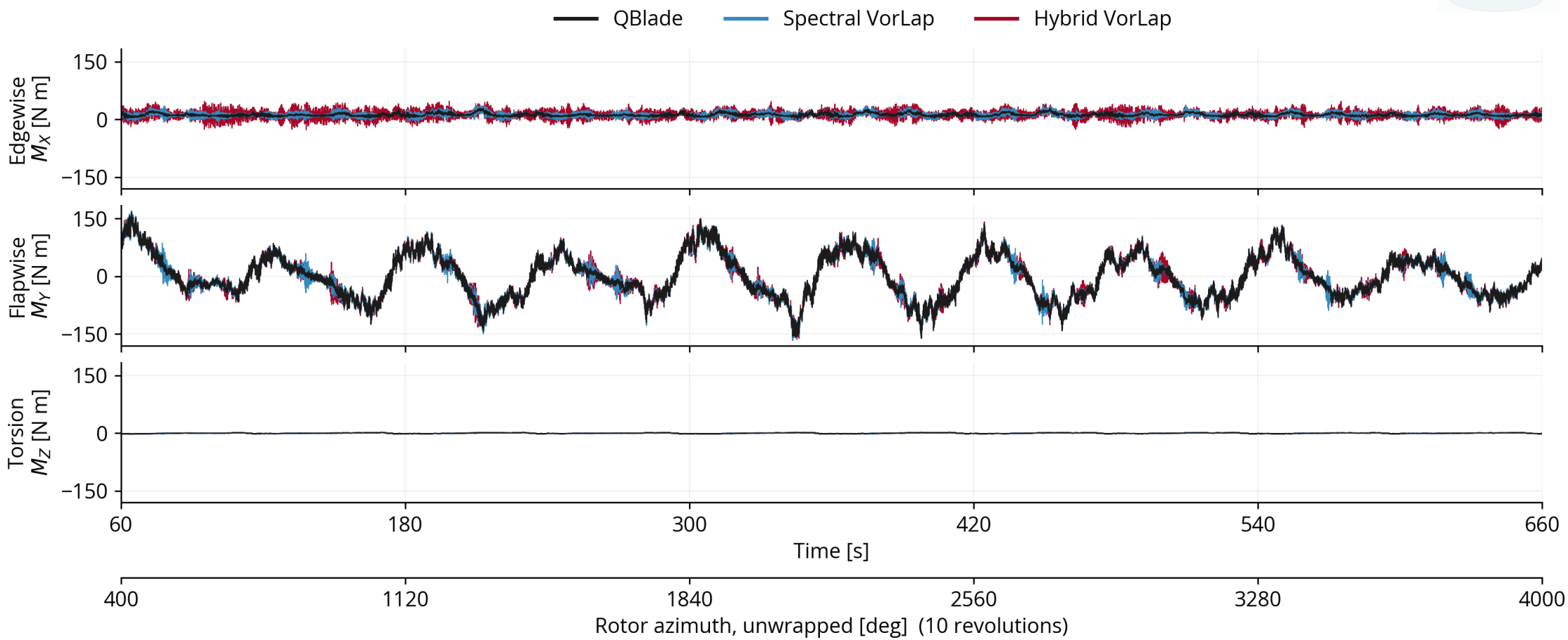
50 m/s · Blade 1, 23% height · seed 5533456 · 620–650 s

Backup: 3 m/s — Full 10-Minute Moment History



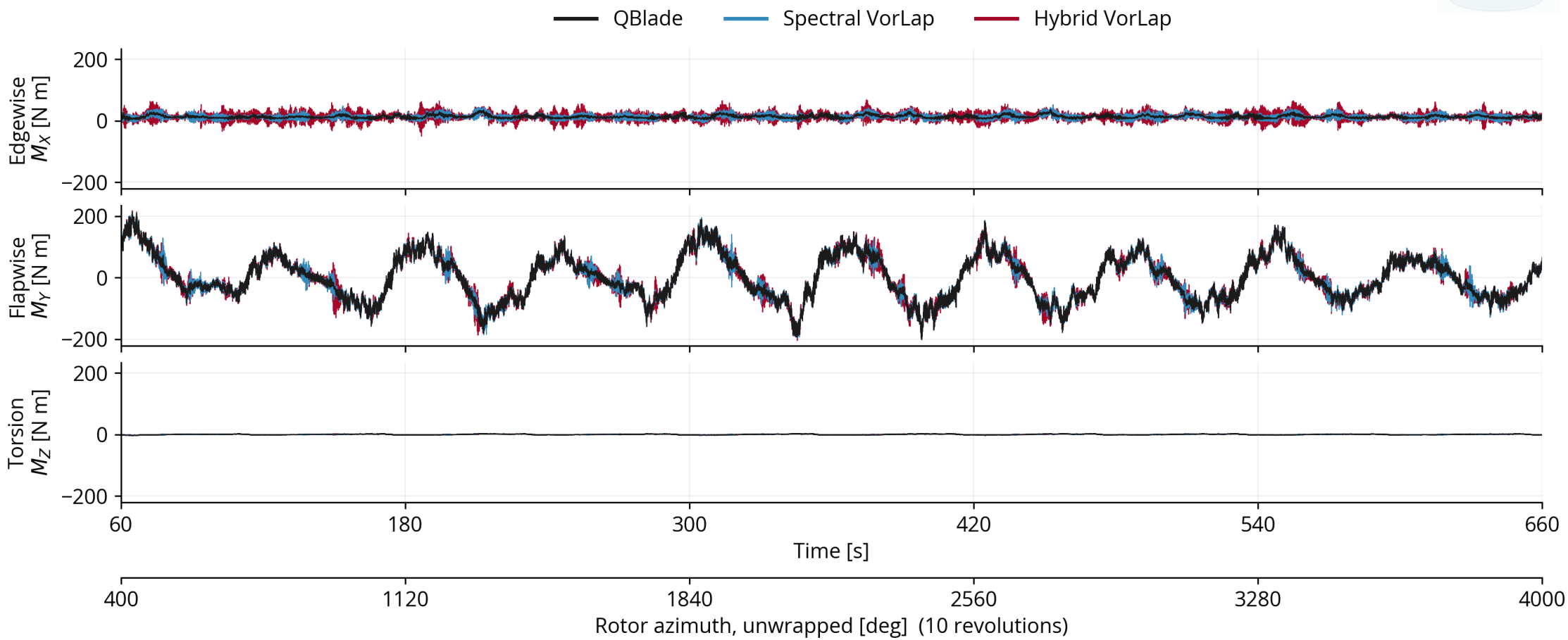
3 m/s · Blade 1, 23% height · seed 4433456 · 60–660 s · 10 revolutions

Backup: 7 m/s — Full 10-Minute Moment History



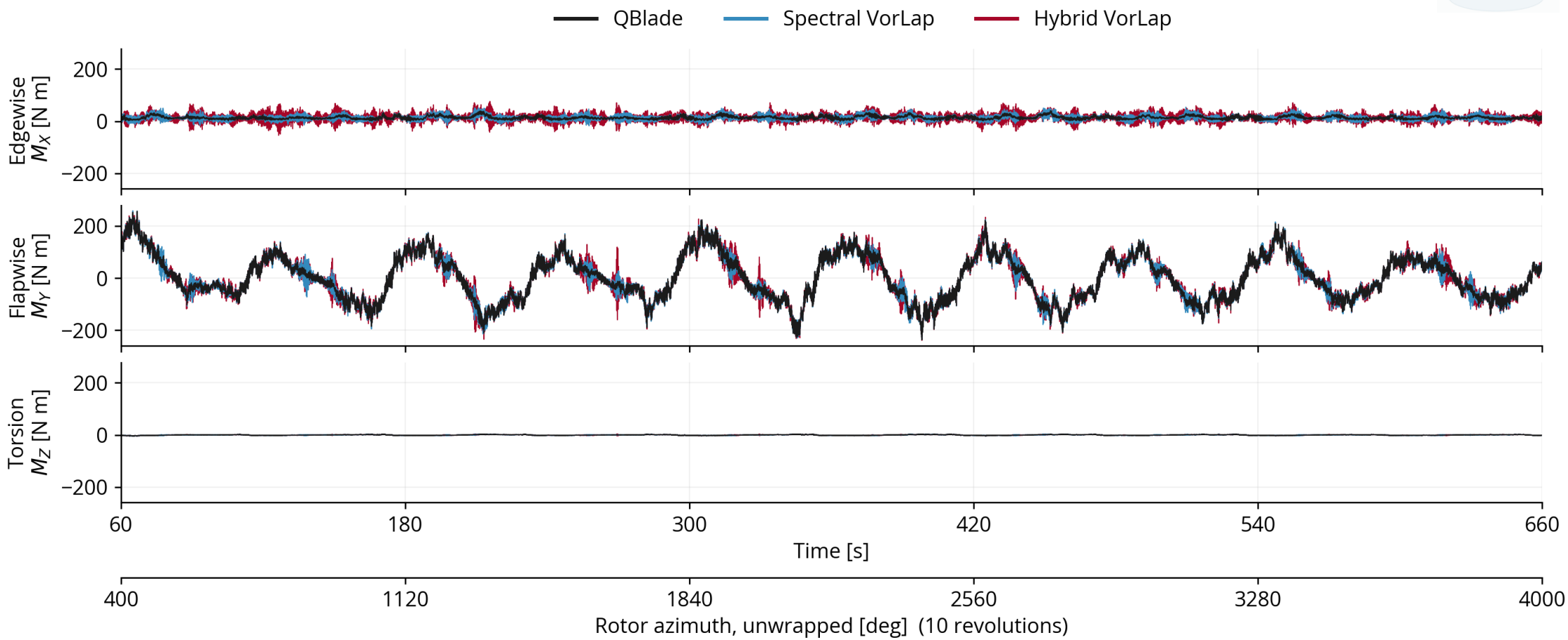
7 m/s · Blade 1, 23% height · seed 4433456 · 60–660 s · 10 revolutions

Backup: 8 m/s — Full 10-Minute Moment History



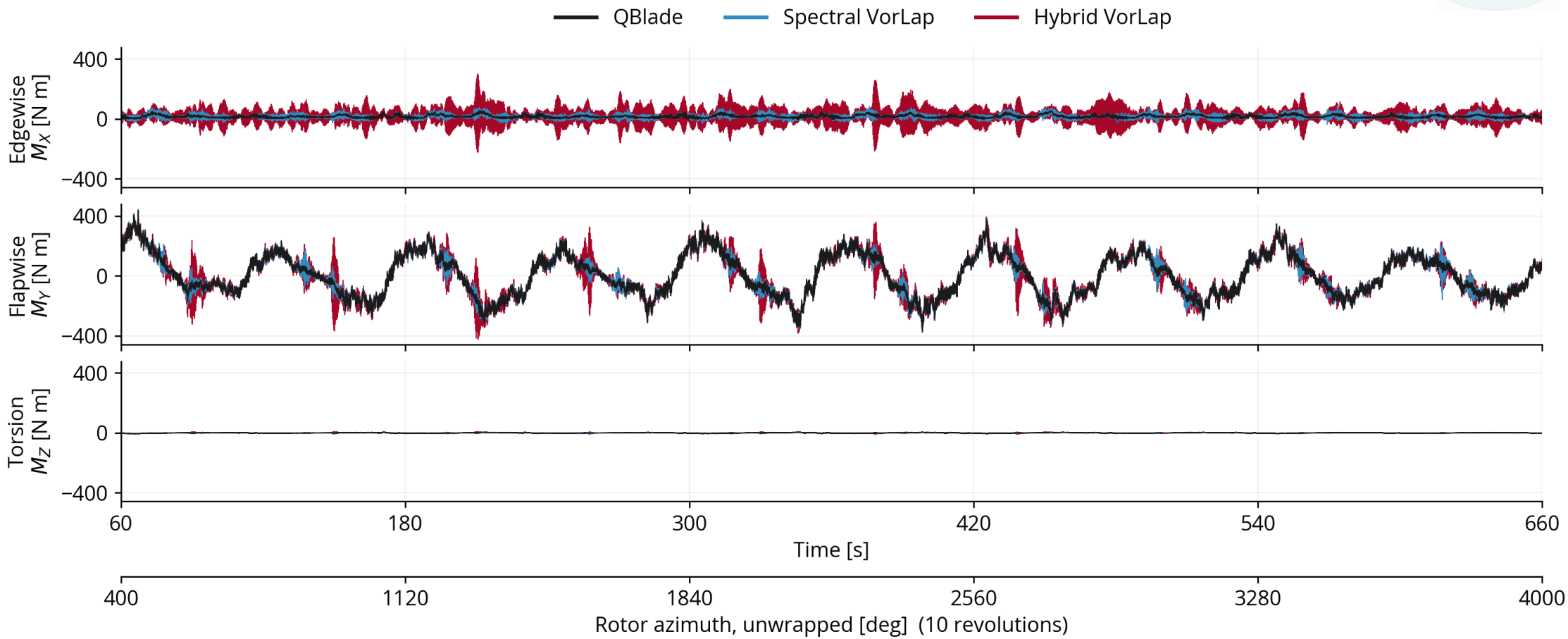
8 m/s · Blade 1, 23% height · seed 4433456 · 60–660 s · 10 revolutions

Backup: 8.75 m/s — Full 10-Minute Moment History



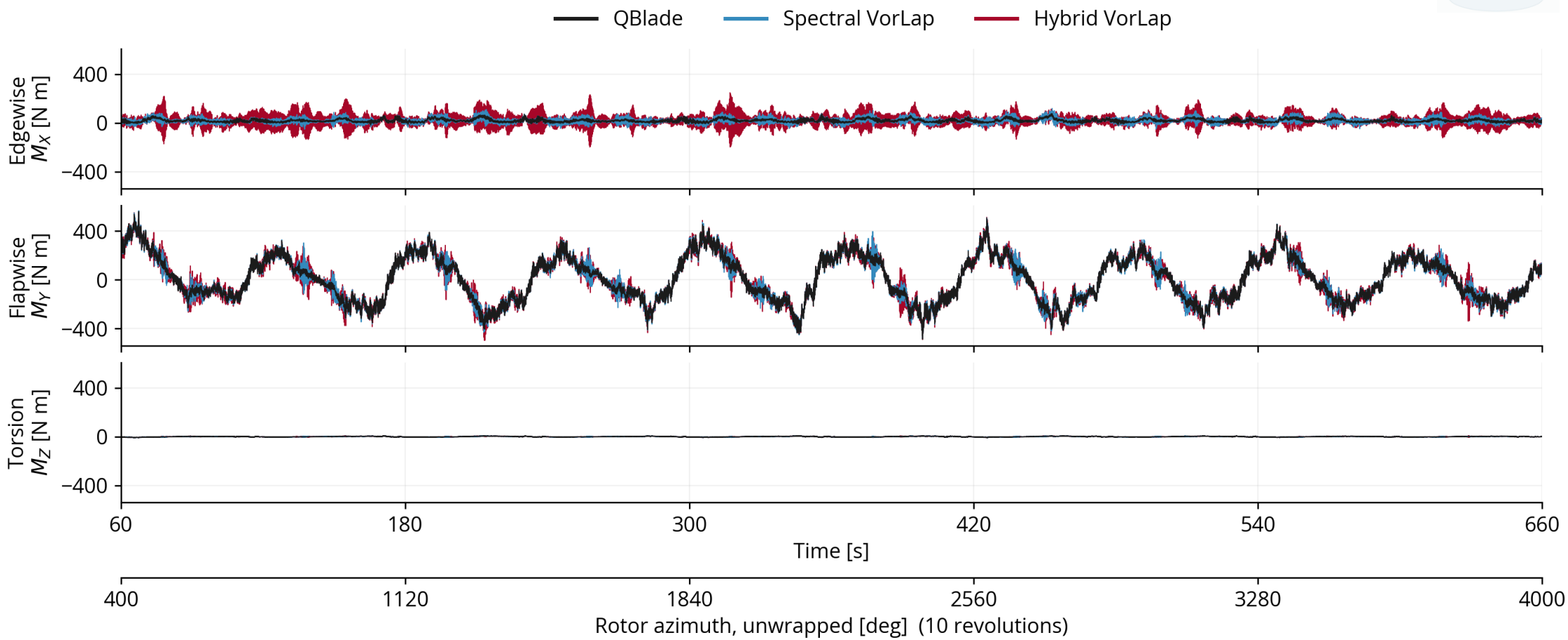
8.75 m/s · Blade 1, 23% height · seed 4433456 · 60–660 s · 10 revolutions

Backup: 11.25 m/s — Full 10-Minute Moment History



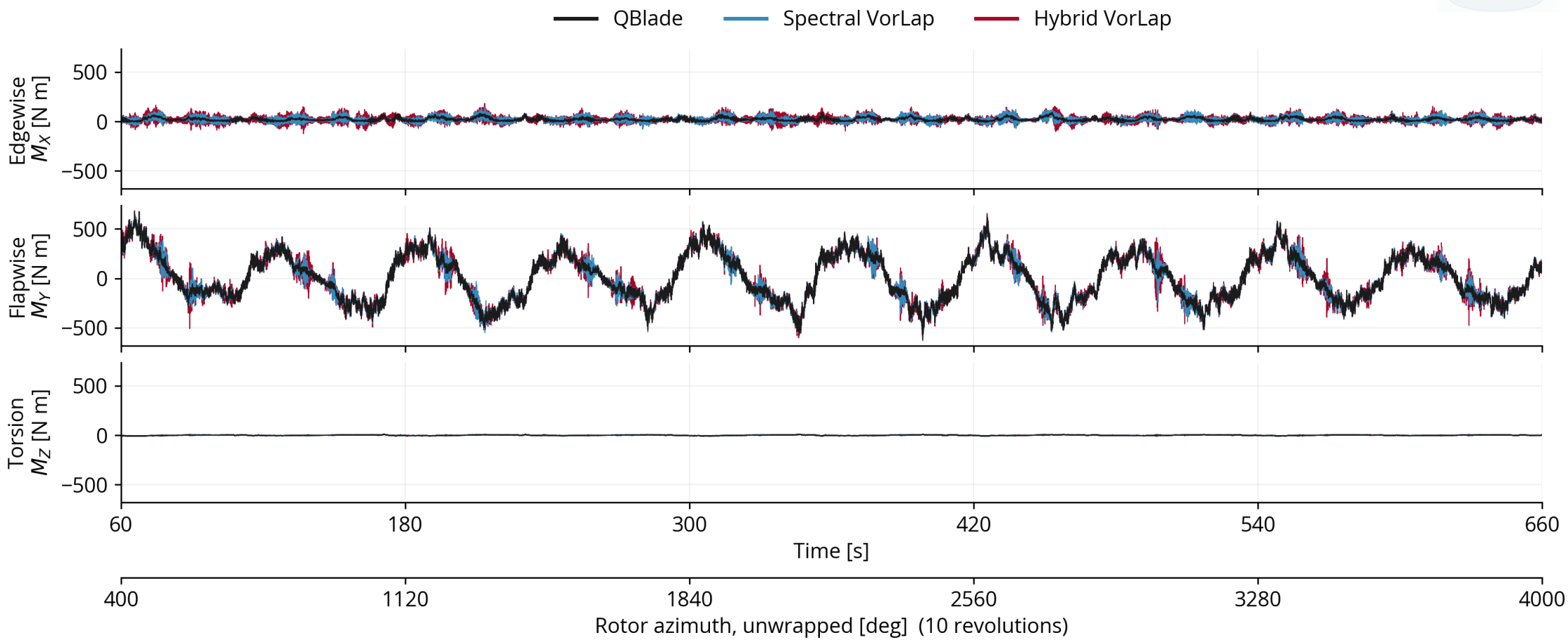
11.25 m/s · Blade 1, 23% height · seed 4433456 · 60–660 s · 10 revolutions

Backup: 13 m/s — Full 10-Minute Moment History



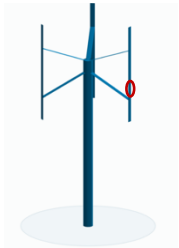
13 m/s · Blade 1, 23% height · seed 4433456 · 60–660 s · 10 revolutions

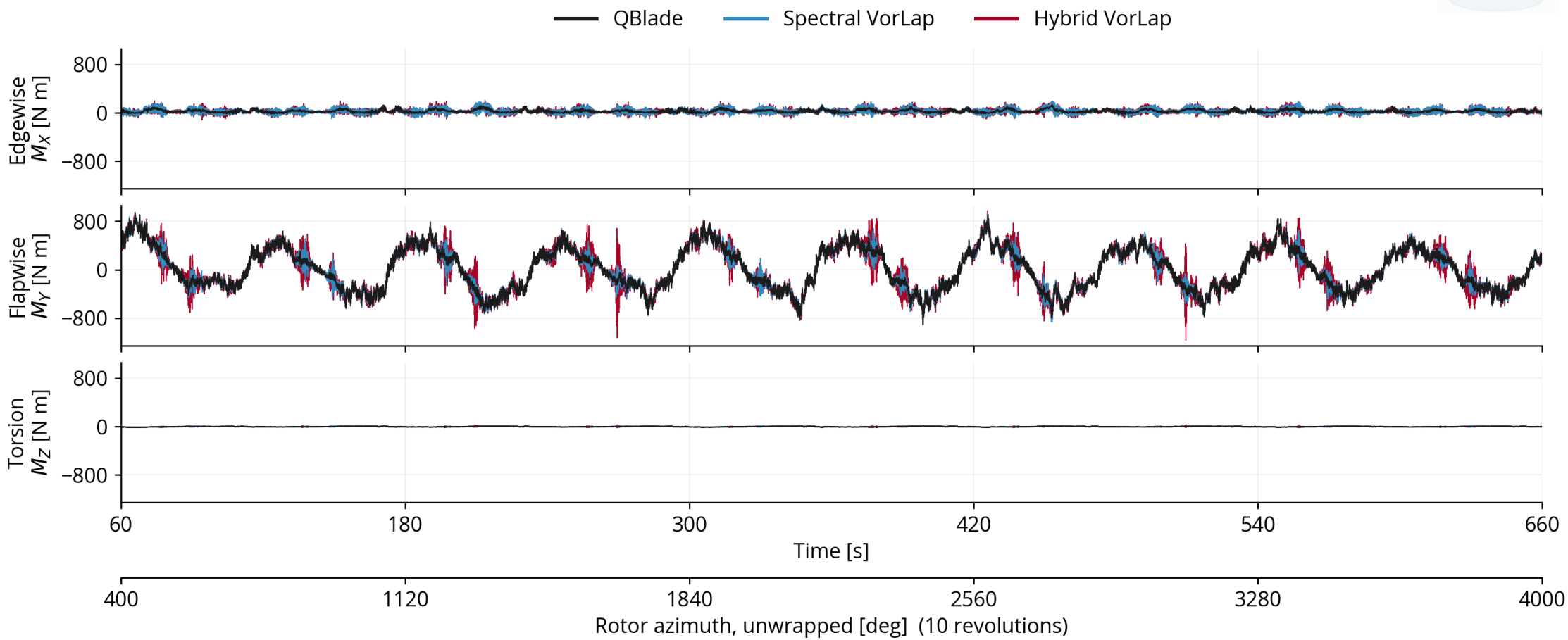
Backup: 14.75 m/s — Full 10-Minute Moment History



14.75 m/s · Blade 1, 23% height · seed 4433456 · 60–660 s · 10 revolutions

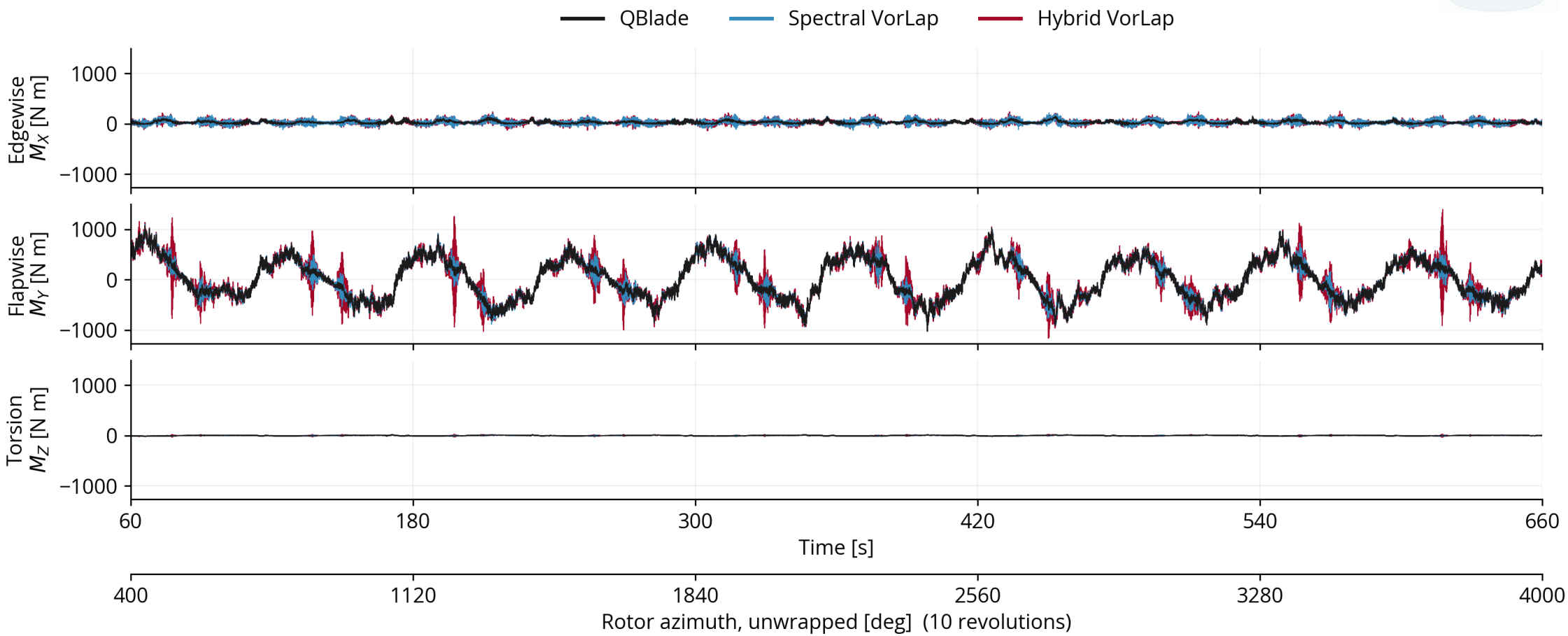
Backup: 18 m/s — Full 10-Minute Moment History





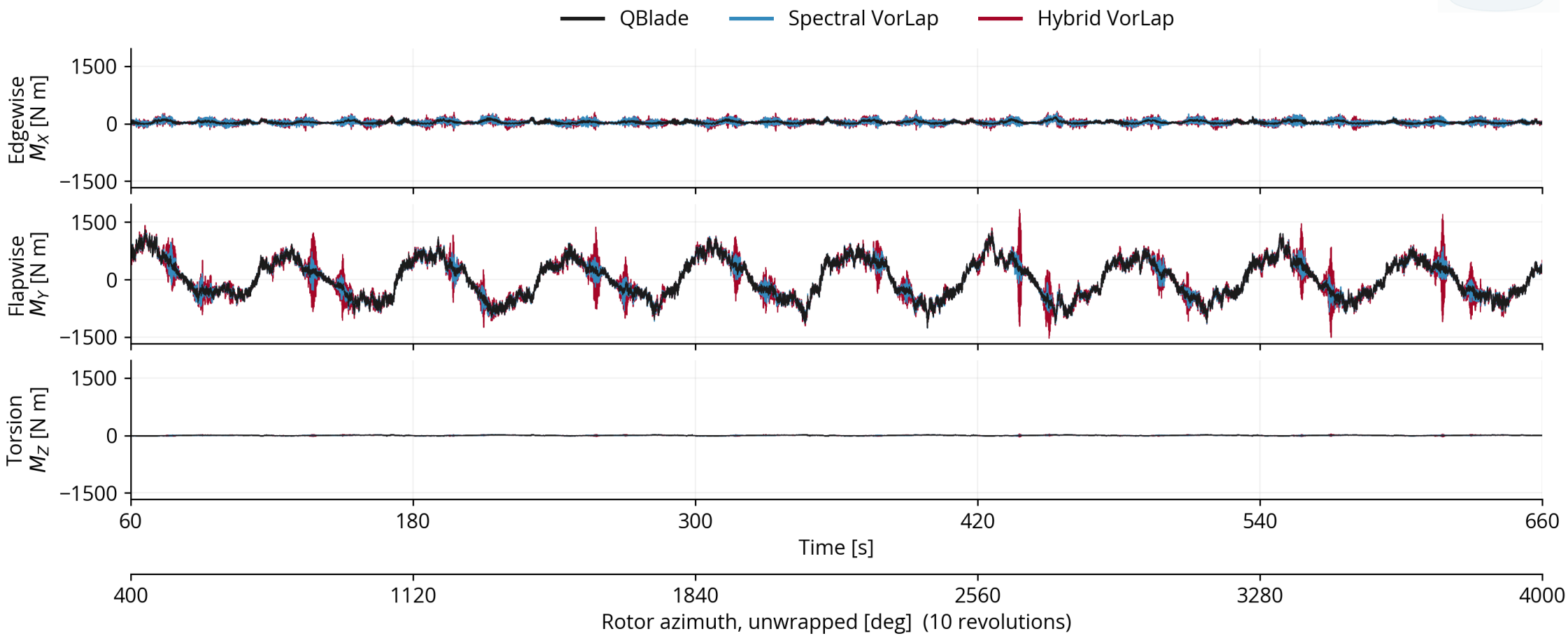
18 m/s · Blade 1, 23% height · seed 4433456 · 60–660 s · 10 revolutions

Backup: 19.25 m/s — Full 10-Minute Moment History



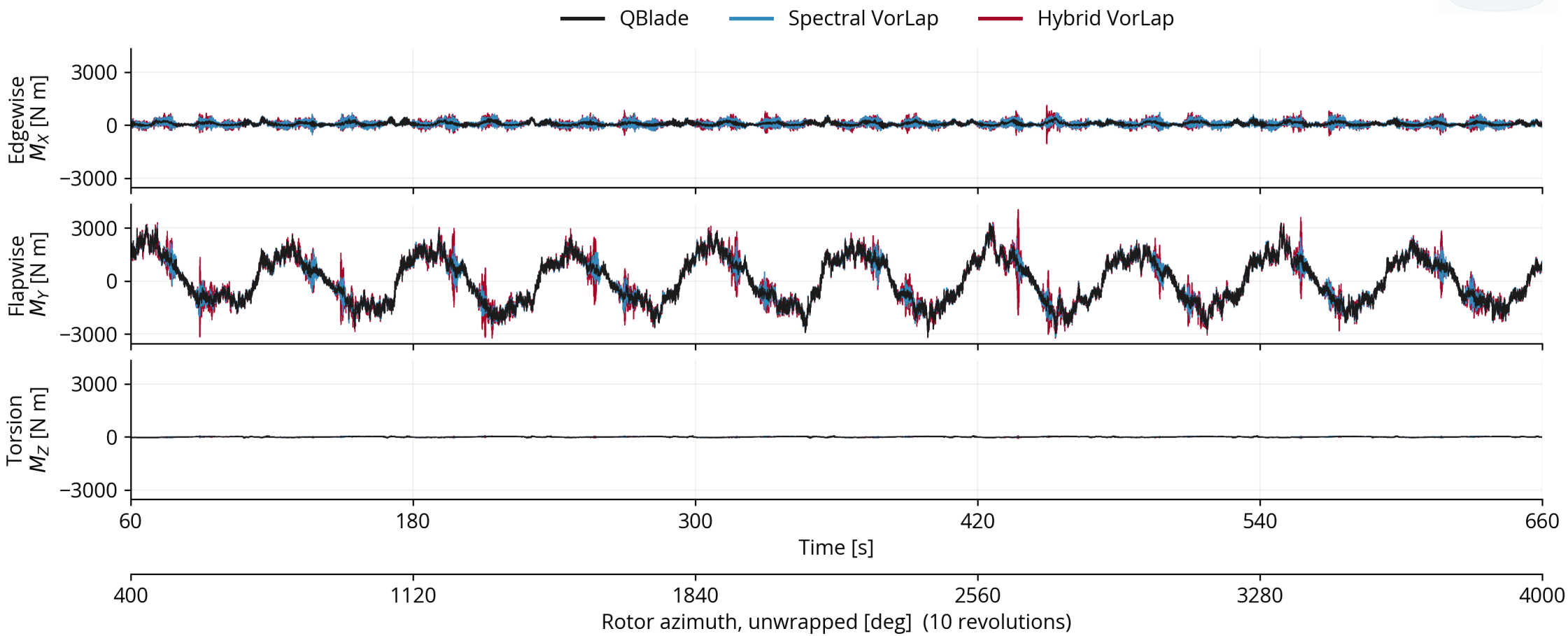
19.25 m/s · Blade 1, 23% height · seed 4433456 · 60–660 s · 10 revolutions

Backup: 21.5 m/s — Full 10-Minute Moment History



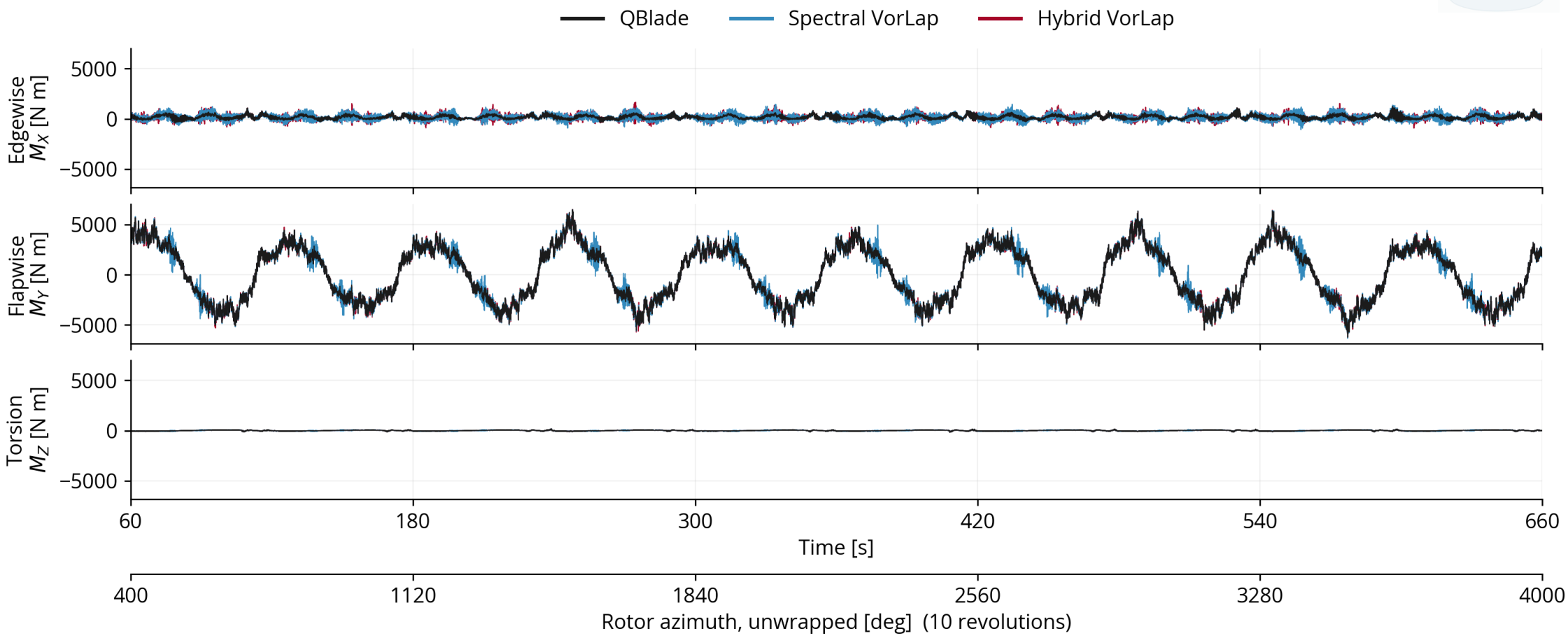
21.5 m/s · Blade 1, 23% height · seed 4433456 · 60–660 s · 10 revolutions

Backup: 35 m/s — Full 10-Minute Moment History



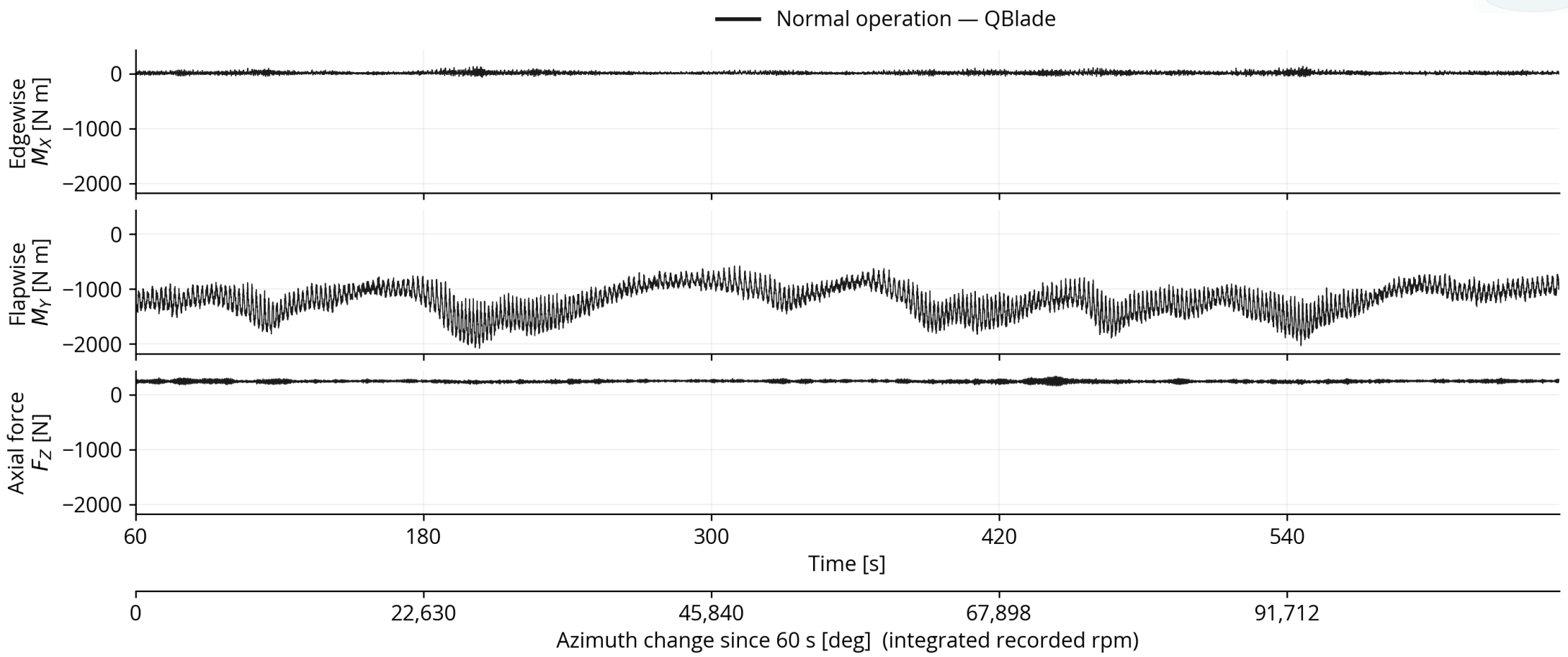
35 m/s · Blade 1, 23% height · seed 4433456 · 60–660 s · 10 revolutions

Backup: 50 m/s — Full 10-Minute Moment History



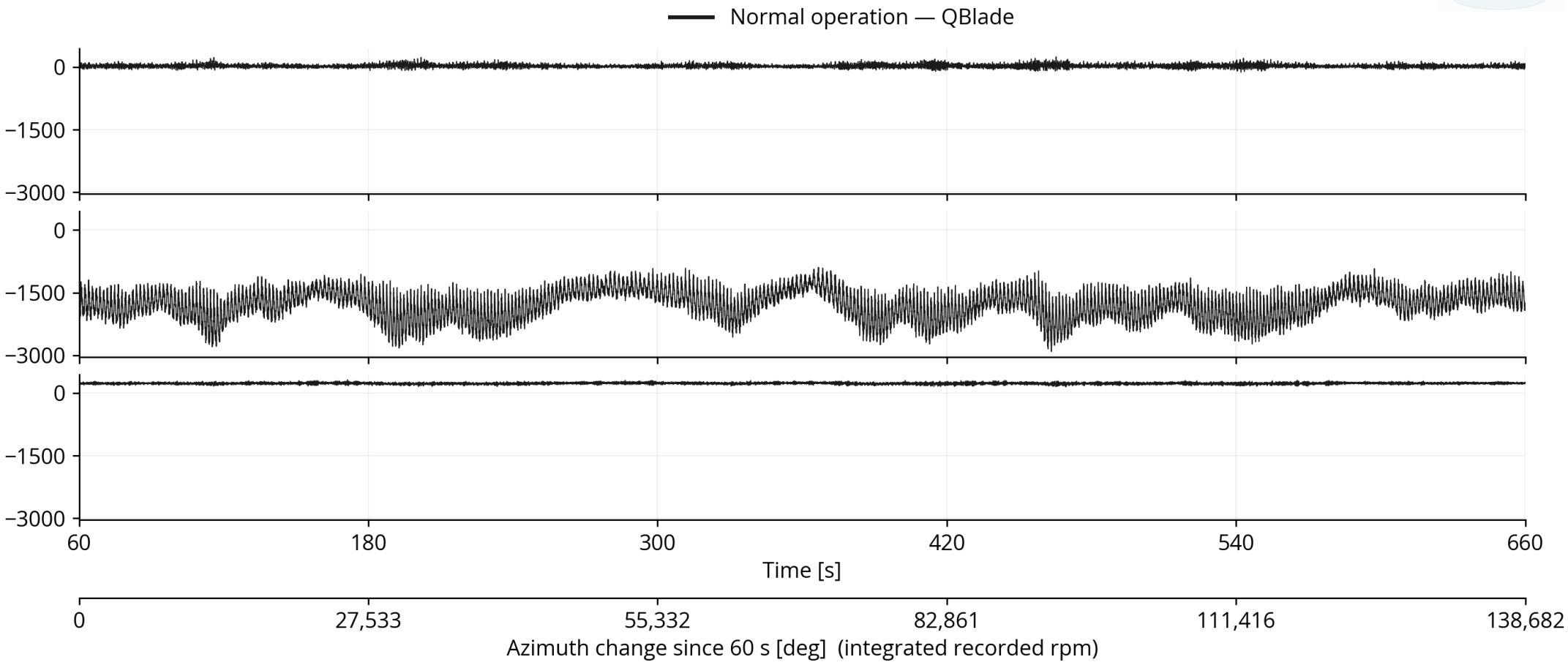
50 m/s · Blade 1, 23% height · seed 5533456 · 60–660 s · 10 revolutions

Backup: Normal Operation at 4 m/s



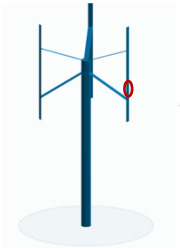
Blade 1, 23% height · seed 4433456 · 593.5 s · wall-time limit

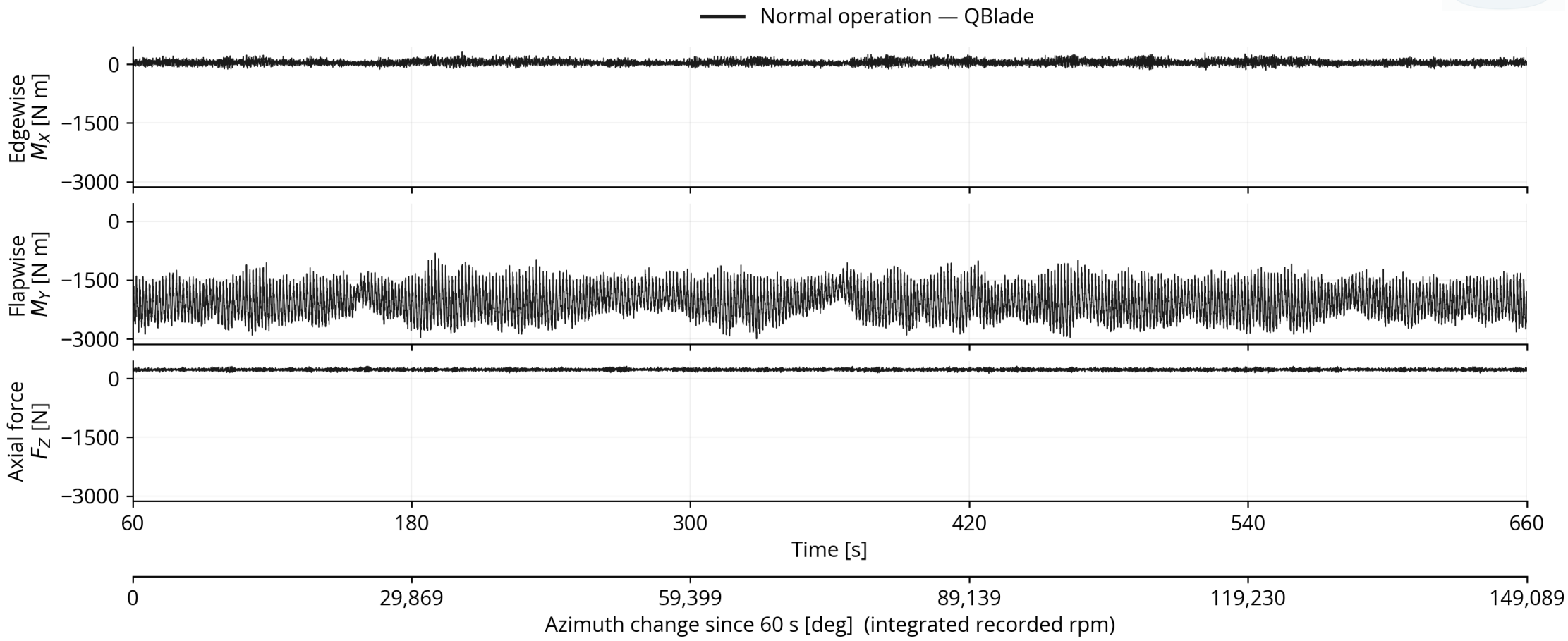
Backup: Normal Operation at 6 m/s



Blade 1, 23% height · seed 4433456 · Full 600 s

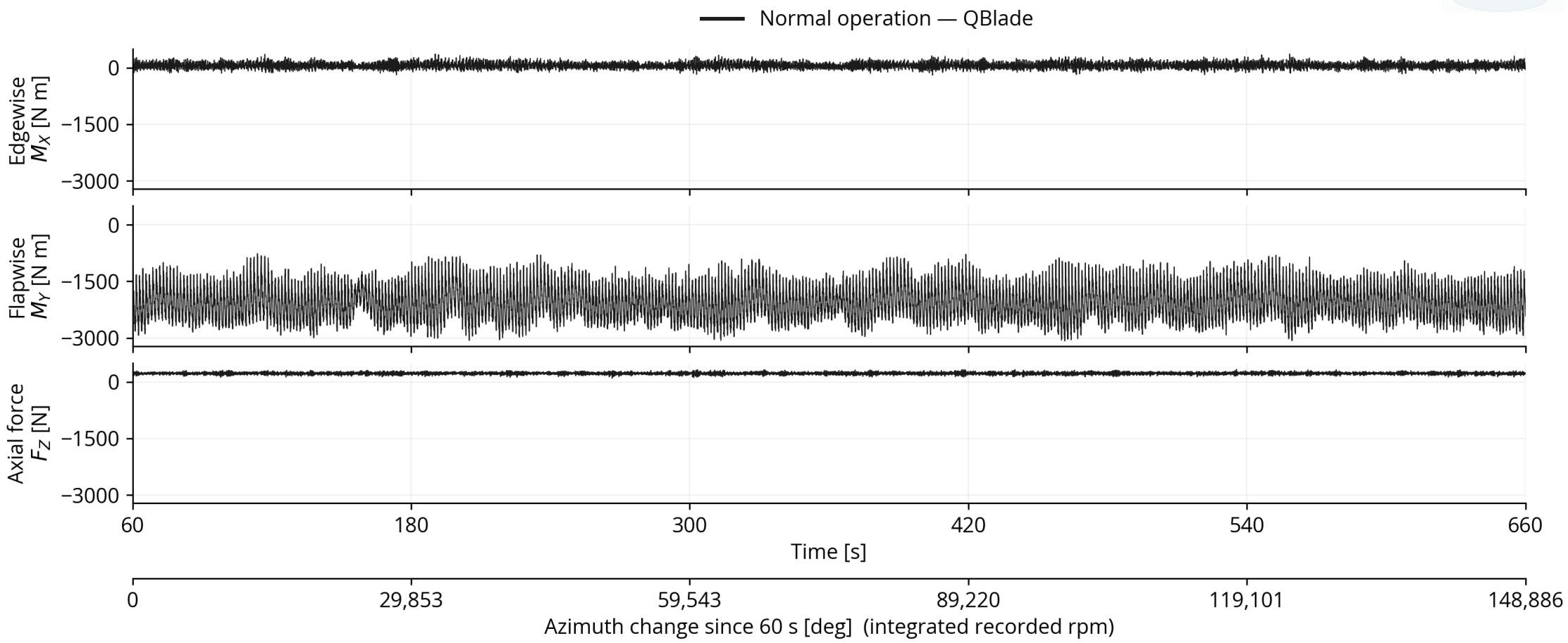
Backup: Normal Operation at 8 m/s





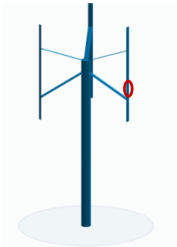
Blade 1, 23% height · seed 4433456 · Full 600 s

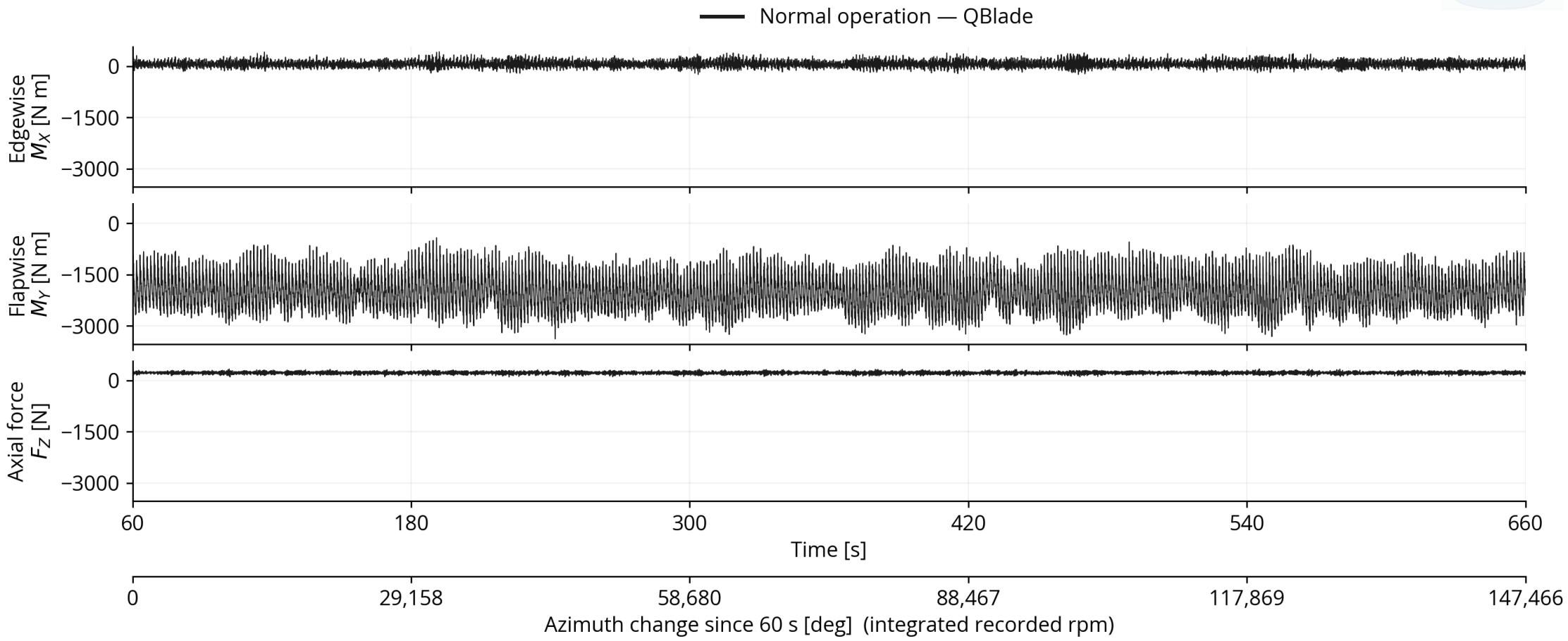
Backup: Normal Operation at 10 m/s



Blade 1, 23% height · seed 4433456 · Full 600 s

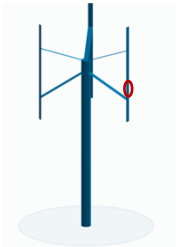
Backup: Normal Operation at 12 m/s

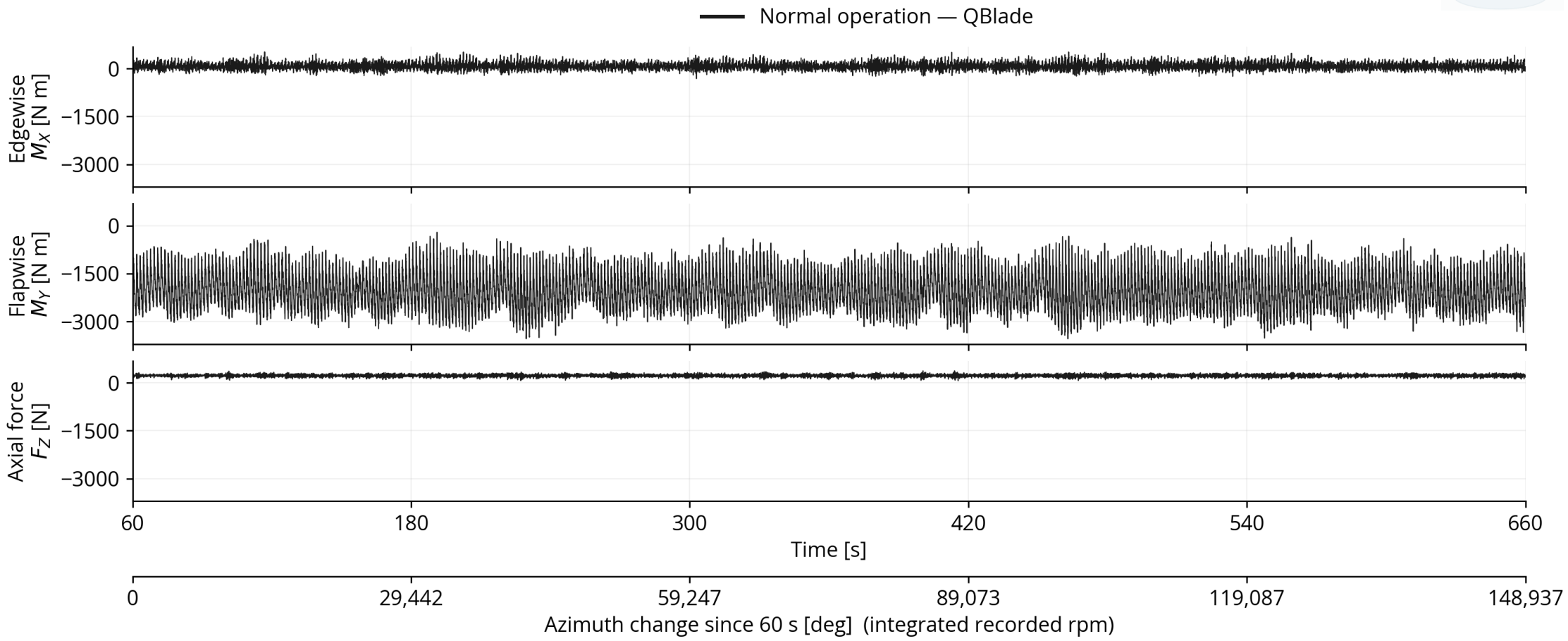




Blade 1, 23% height · seed 4433456 · Full 600 s

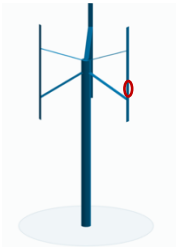
Backup: Normal Operation at 14 m/s

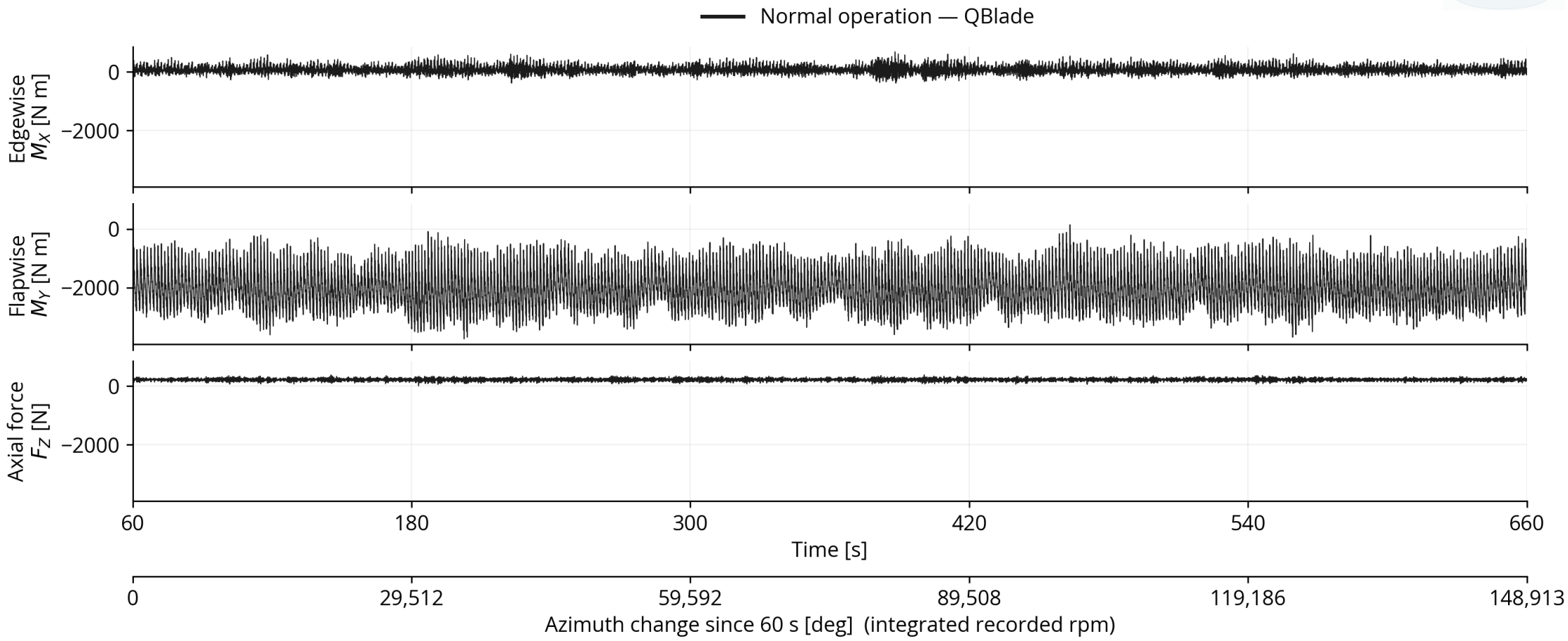




Blade 1, 23% height · seed 4433456 · Full 600 s

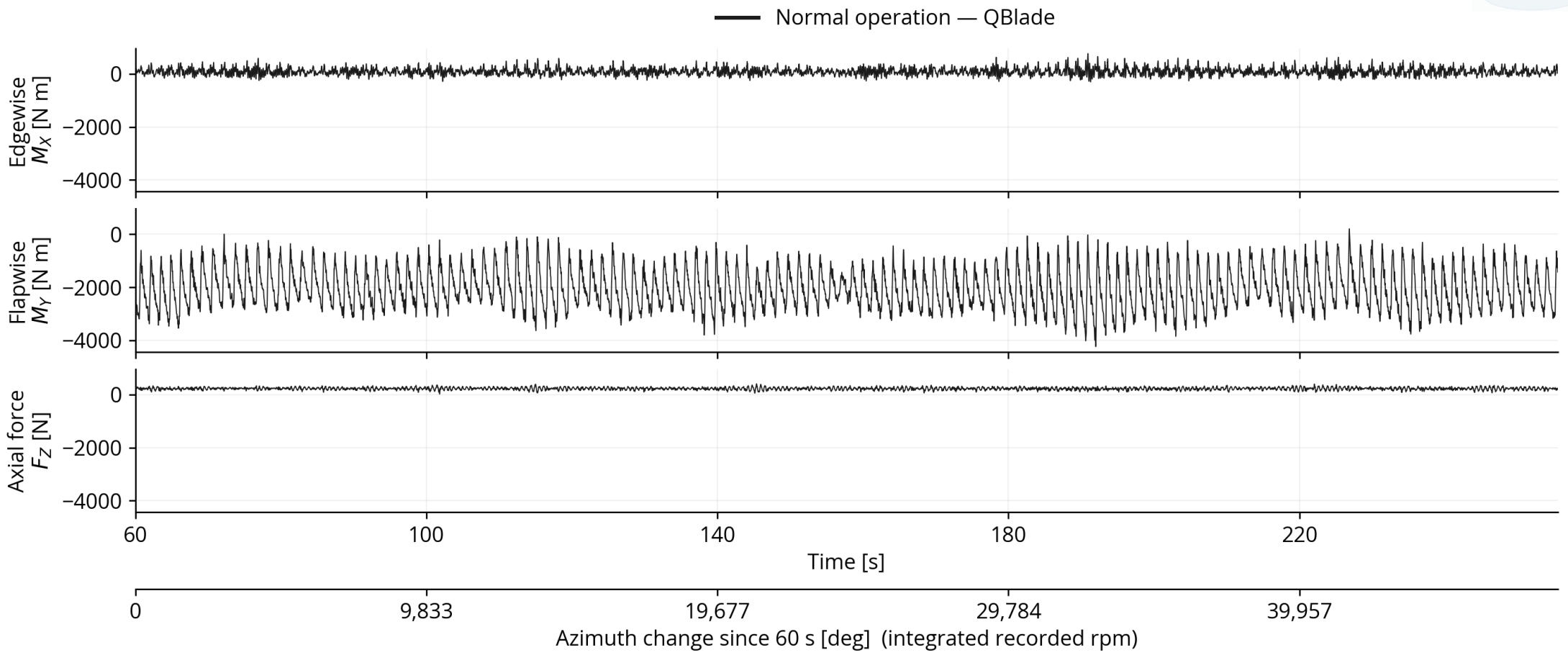
Backup: Normal Operation at 16 m/s





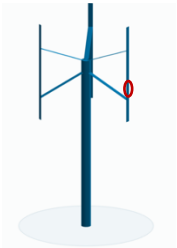
Blade 1, 23% height · seed 4433456 · Full 600 s

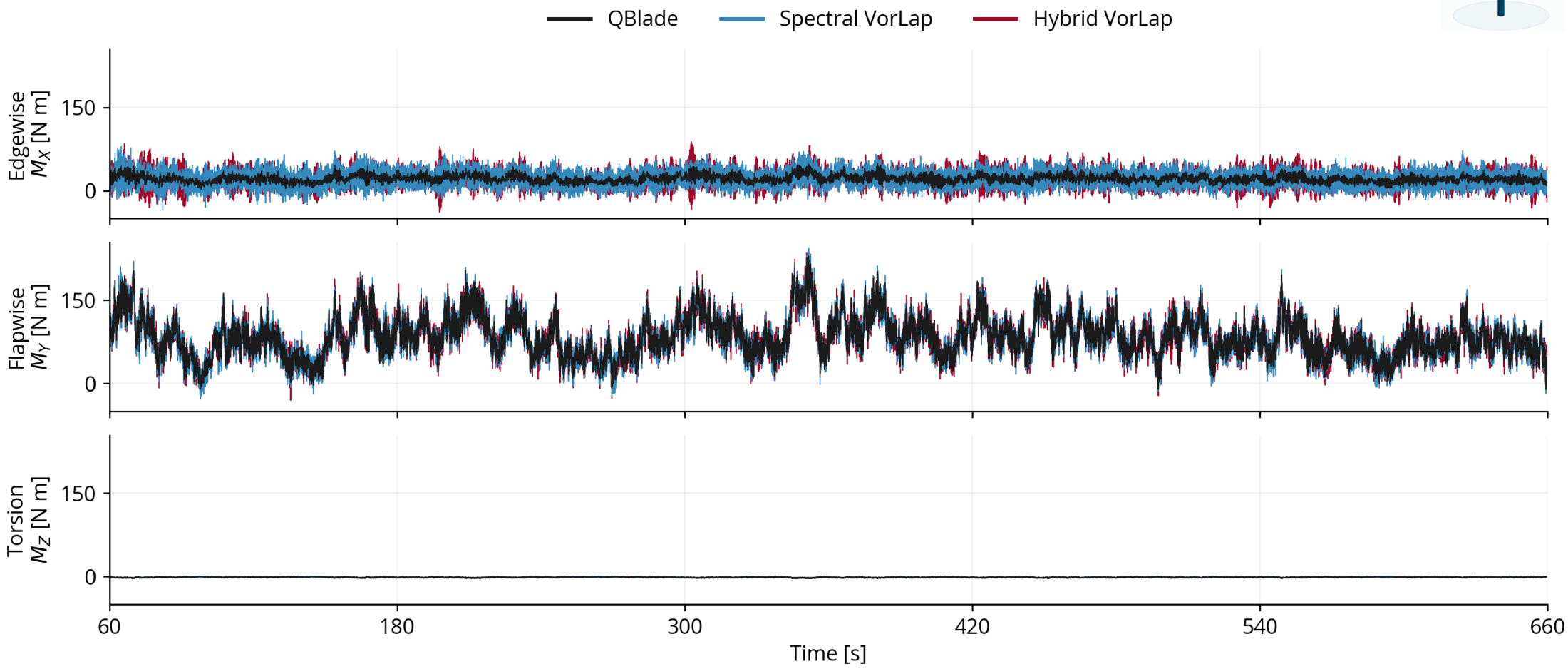
Backup: Normal Operation at 17.5 m/s



Blade 1, 23% height · seed 4433456 · 195.5 s · solver stopped

11.25 m/s — Fixed 147° Moment History

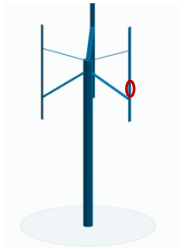


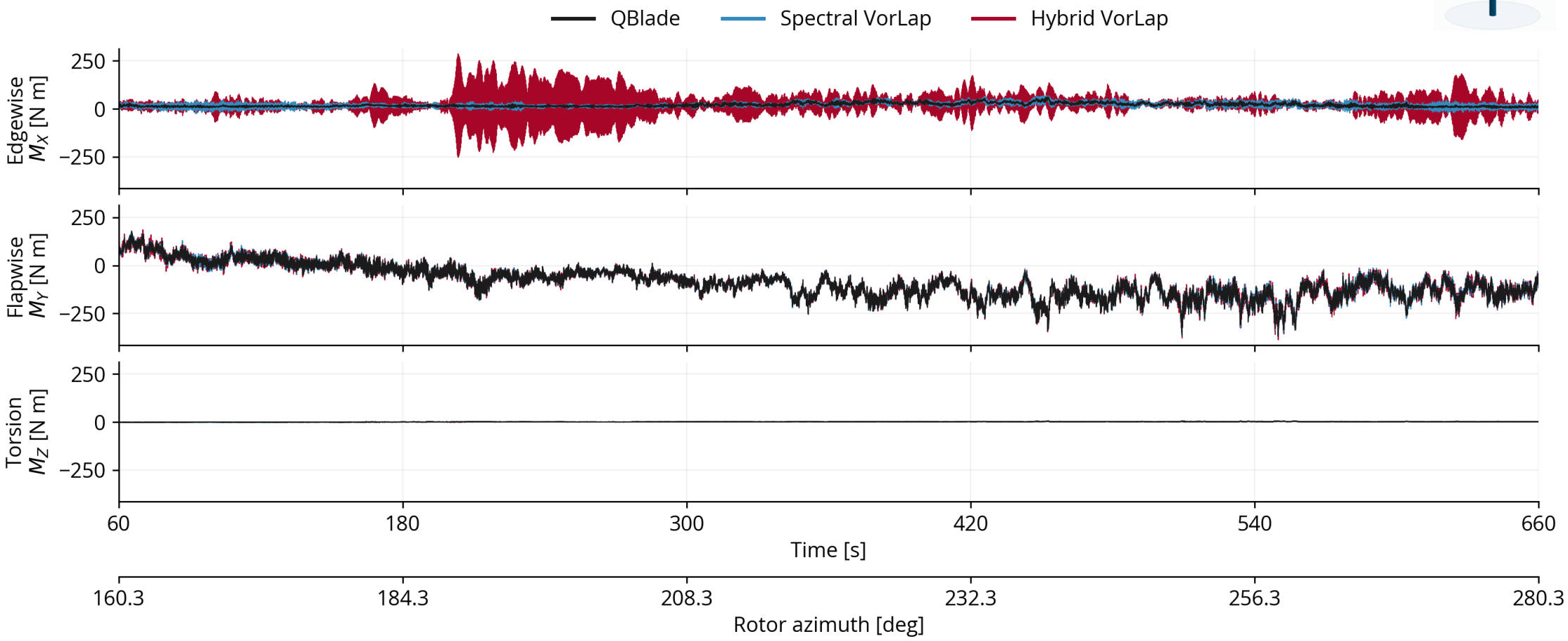


Hybrid / QBlade fluctuation RMS: 2.53× edgewise · 1.03× flapwise

0 rpm · Blade 1, 23% height · seed 4433456 · 60–660 s retained

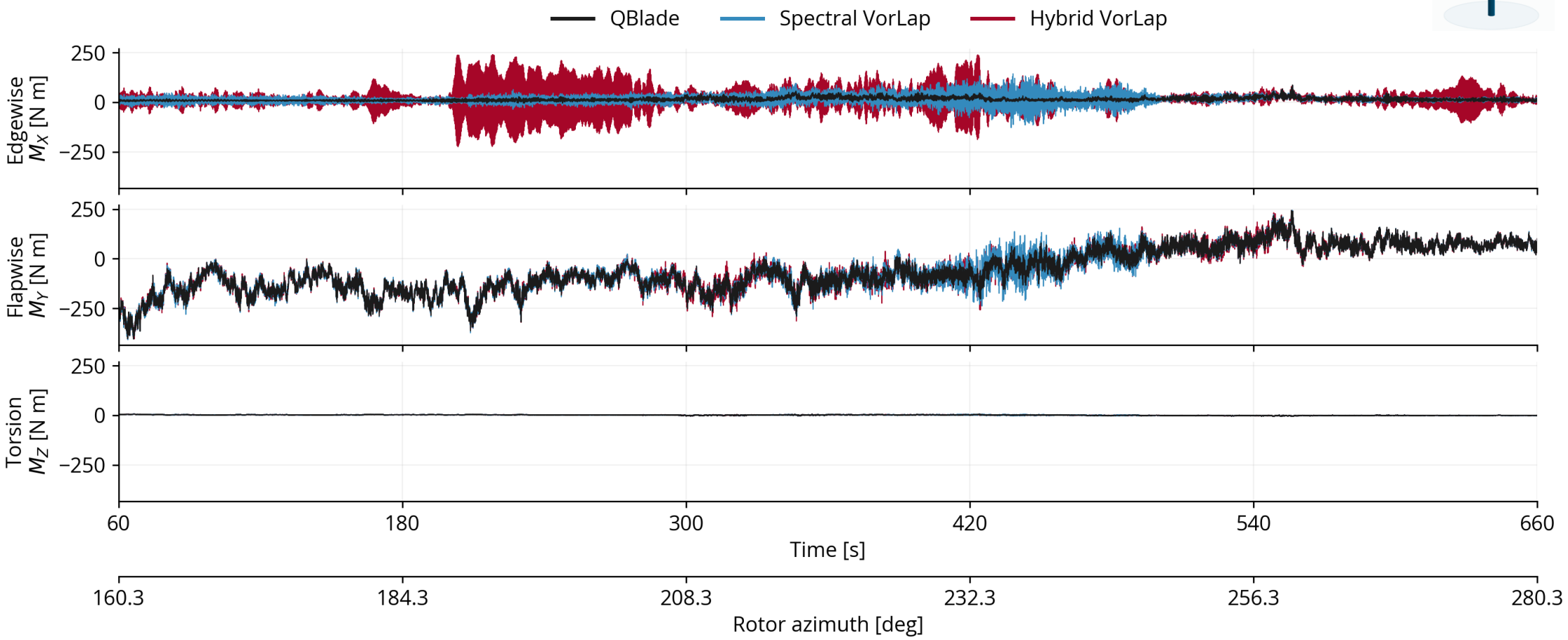
11.25 m/s — Slow Sweep, Blade 1





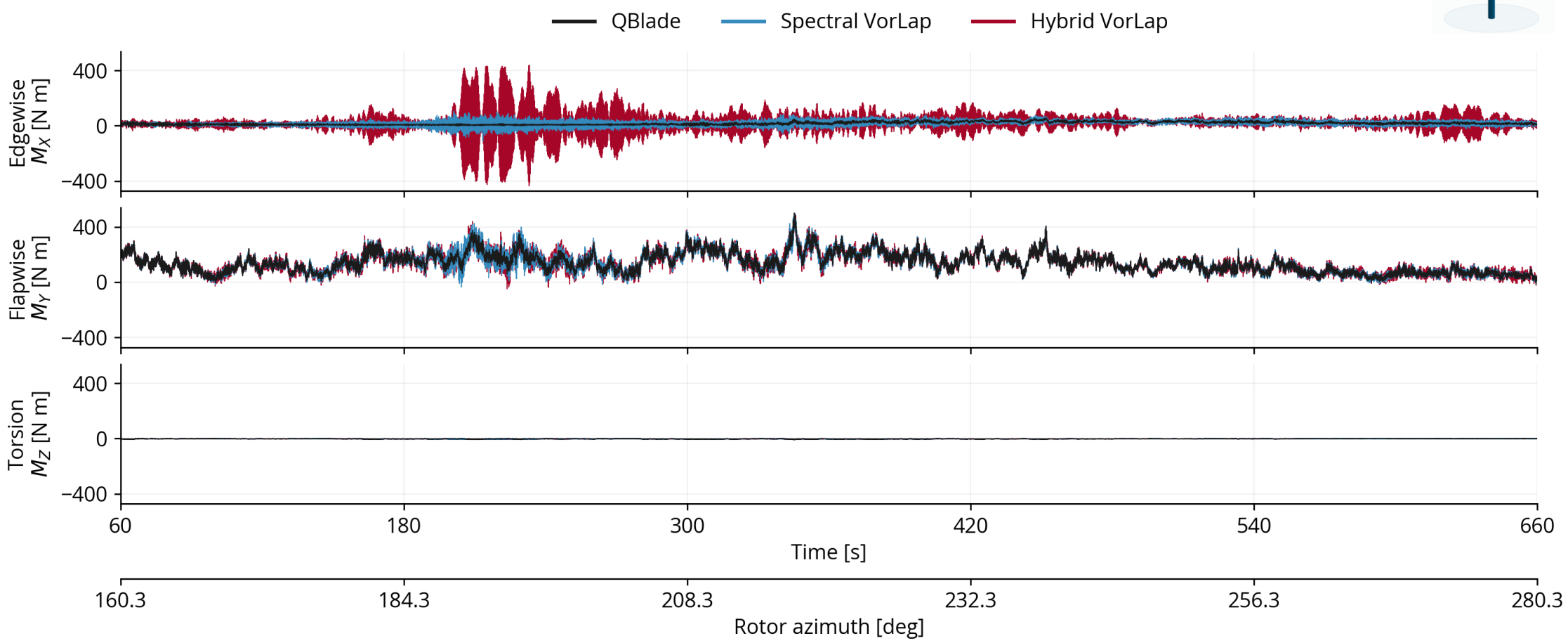
0.03333 rpm · Blade 1, 23% height · seed 4433456 · 60–660 s retained

11.25 m/s — Slow Sweep, Blade 2



0.03333 rpm · Blade 2, 23% height · seed 4433456 · 60–660 s retained

11.25 m/s — Slow Sweep, Blade 3



Hybrid longitudinal damage rate: 83% lower than the 1-rpm average

Worst 10° window (188.5–198.5°), Blade 3 vs full-record Blade 1 · finite-record estimate

0.03333 rpm · Blade 3, 23% height · seed 4433456 · 60–660 s retained