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Simulation and Modeling of Power Take-Off Dynamics in Floating Axis Wind Turbine

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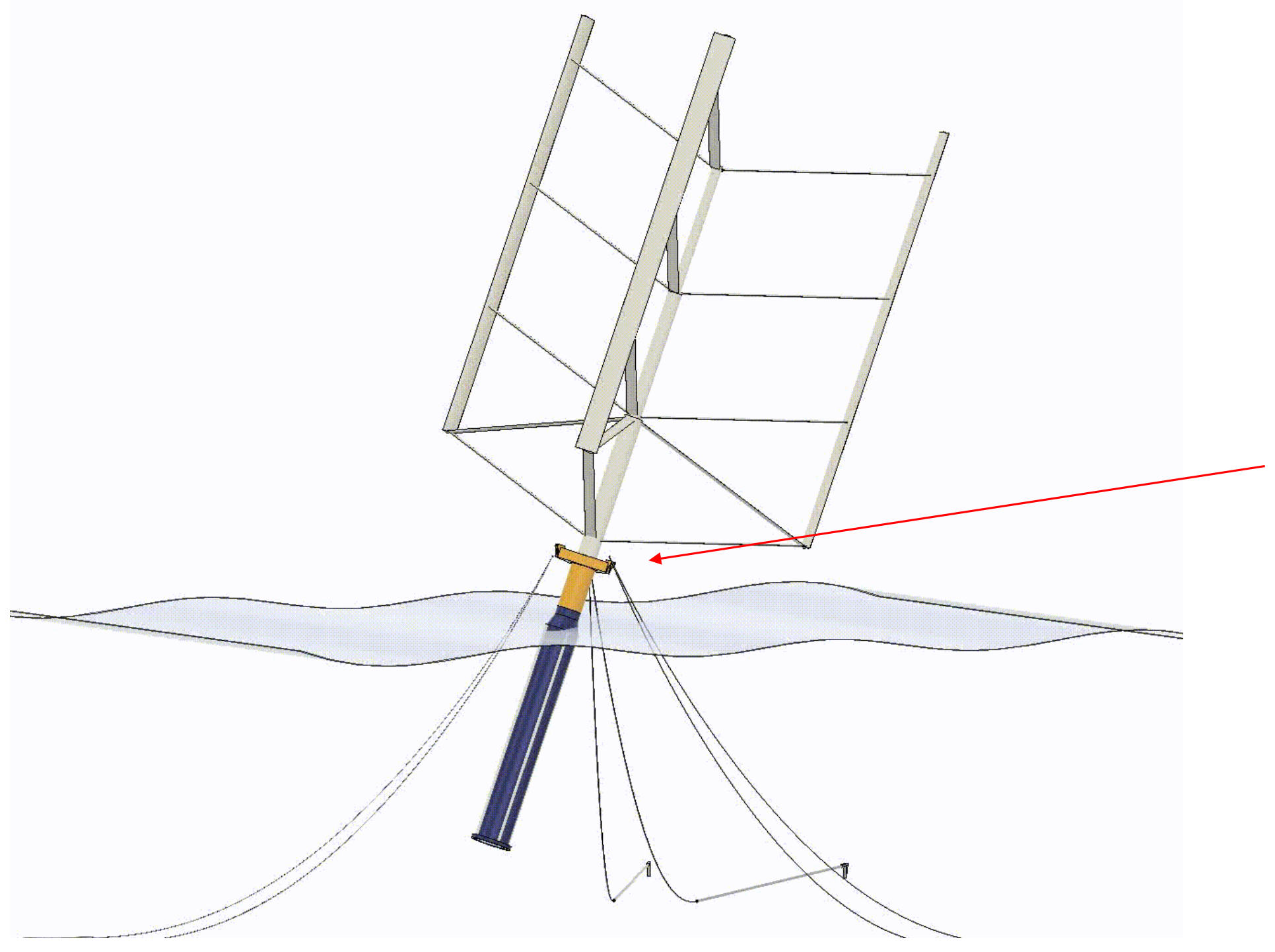
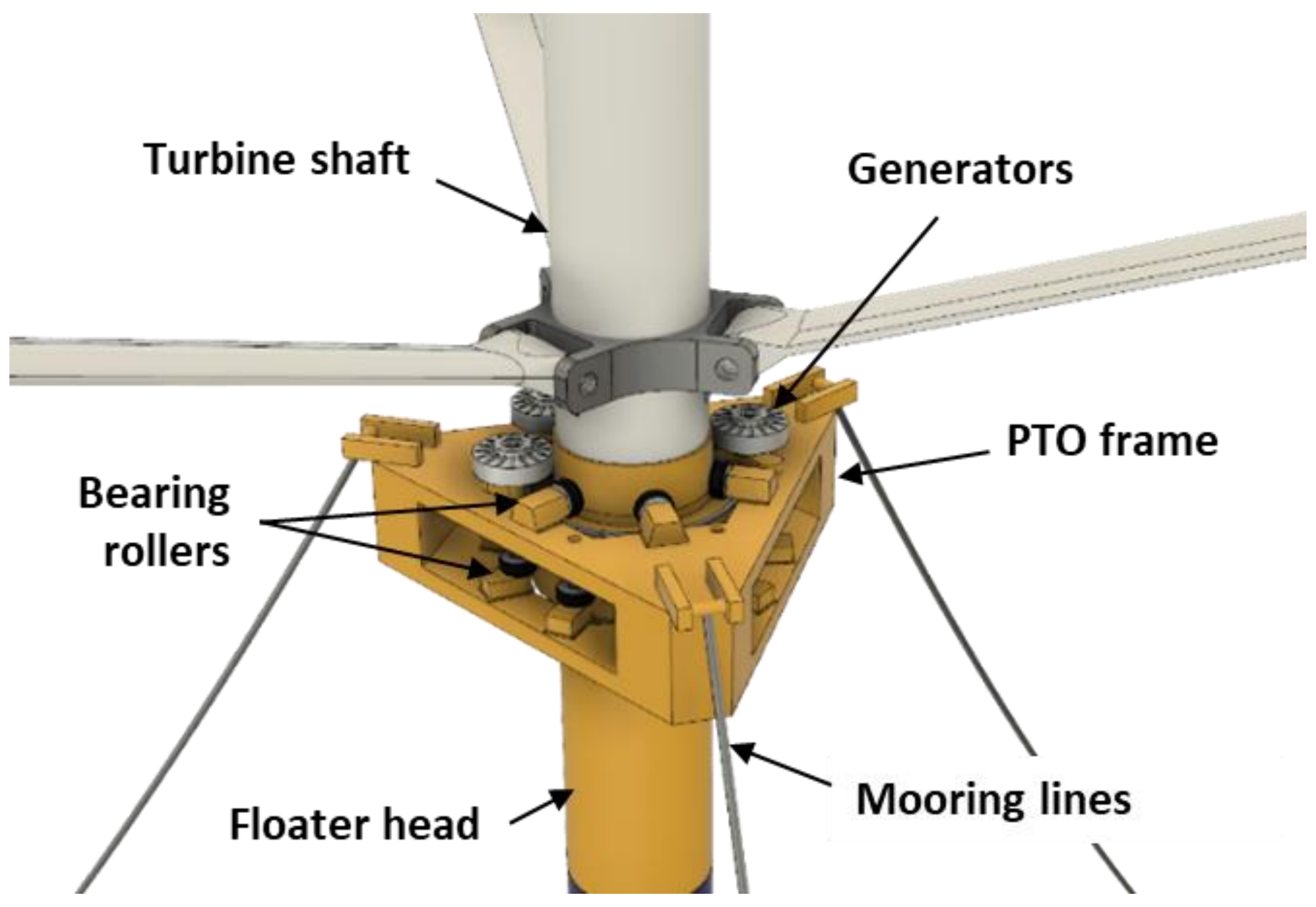
Background and Objective

Vertical axis wind turbines (VAWT) generate power are quieter, more cost-effective, and have a low center of gravity, but generally offer lower performance than horizontal axis wind turbines (HAWT). However, larger VAWTs can achieve efficiencies comparable to HAWTs, making them a future option.

In a typical floating VAWT, the float and power take-off (PTO) unit operate as a single unit, whereas in a floating axis wind turbine (FAWT), the PTO is independent of the float. This smaller PTO enhances maintainability and durability. Multiple generators around the float reduce mass and moment of inertia, allowing for high responsiveness to torque fluctuations. Understanding the dynamics of the PTO is crucial for efficient yaw rotational control.



Description of Floating Axis Wind Turbine



Example of Power Take-Off structure

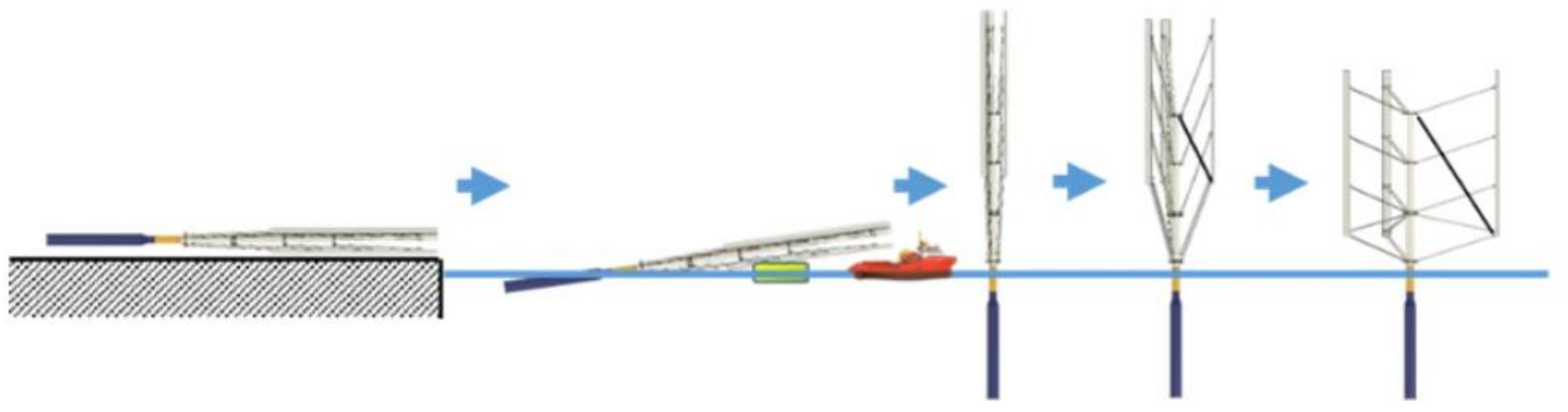
~ What is beneficial of FAWT? ~

Wind Turbine
- does not have pitch control system.
- can keep performance even in inclination.
- can devide some parts for delivering and manufacturing.
- has straight blade which can create easier.

Generator
- is located near sea level contributing lower O&M cost.

Floater
- has spar-shape and rotates with wind turbine.
- get smaller thanks to allowance of pitch angle 20 degrees.

Construction
- can be towed and installed without big ship.

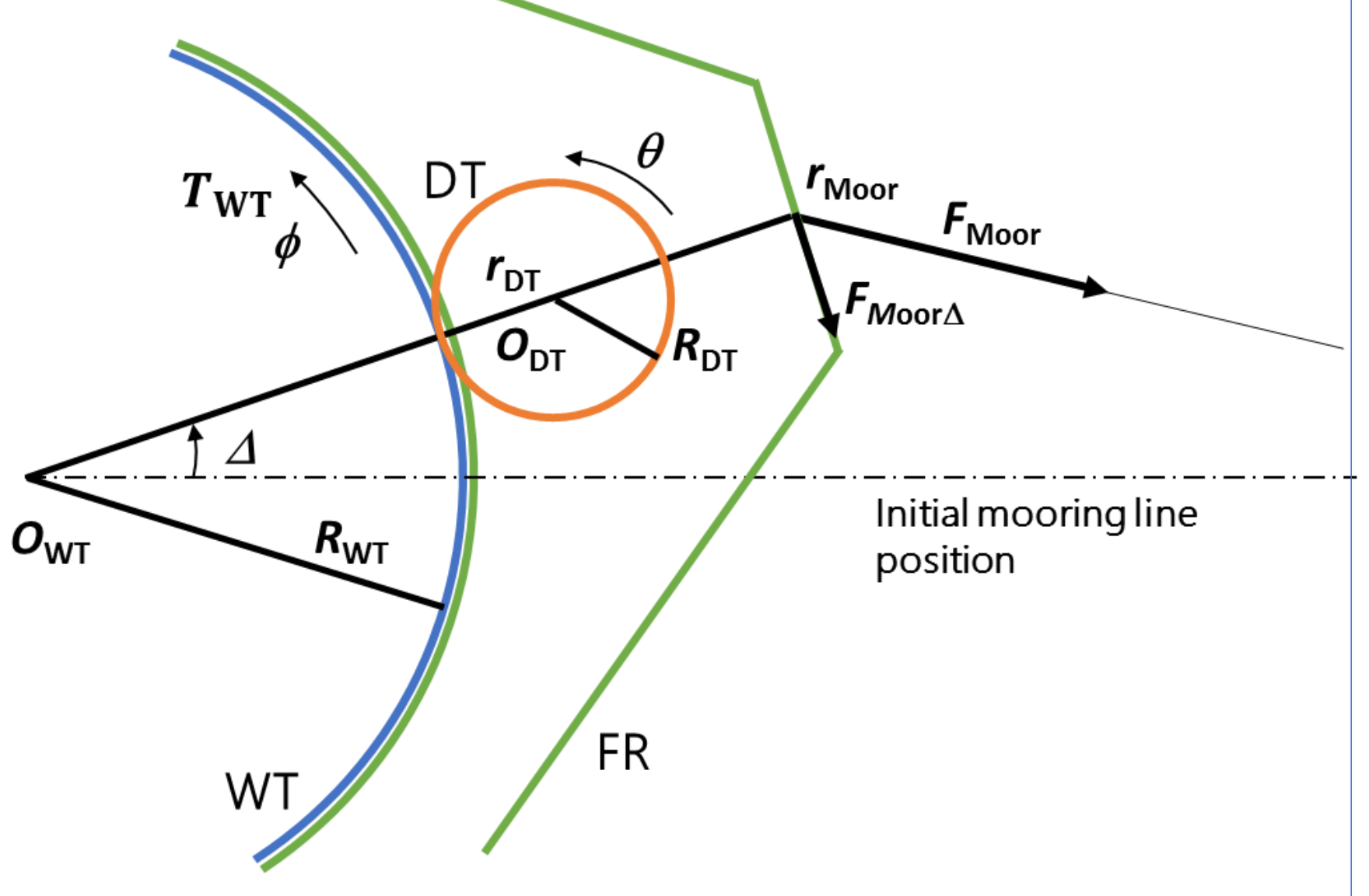


Concept of how to construct FAWT

Power Take-Off Dynamics

~ Assumptions ~

- WT, DT, FR rotates around WT axis.
- DT also rotates around DT axis.
- Non-slip between WT and DT rotation.
- DT axis and mooring coordinates are fixed with FR moving frame.
- Inertia of DT around WT axis includes inertia of FR.
- Every forces and torques are act in the same plane.
- Adopted mooring tension is projected component to the plane.
- Axis of WT considers surge, sway and tilt angle.



Definitions of PTO dynamics model

Forced rotation

Consider only the equation of motion(EOM) for FR.

$$I_{\mathrm{FR}}\frac{d^2\mathit{\Delta}}{dt^2}=\underbrace{\zeta\left(\frac{d\phi}{dt}-\frac{d\mathit{\Delta}}{dt}\right)}_{\text{Generator Torque}}+\underbrace{r_{\mathrm{Moor}}\sum_{i=1}^{N_{\mathrm{Moor}}}F_{\mathrm{Moor}\mathit{\Delta},i}}_{\text{MooringTorque}}\qquad(1)$$

Here, ζ is the damping coeff. due to generators, etc. The damping coefficient can be estimated from the rated operating torque and rotational speed as following,

$$T_{\mathrm{WT}}=\zeta\frac{d\phi}{dt}=r_{\mathrm{Moor}}\sum_{i=1}^{N_{\mathrm{Moor}}}F_{\mathrm{Moor}\mathit{\Delta},i}\qquad(2)$$

WT-FR model

The simplest method to estimate the free rotation. Ignoring the presence of DT and FR inertia, the EOM for WT is as follows.

$$\underbrace{I_{\mathrm{WT}}\frac{d^2\phi}{dt^2}}_{\text{WT intertia}}=T_{\mathrm{WT}}-\underbrace{\zeta\left(\frac{d\phi}{dt}-\frac{d\Delta}{dt}\right)}_{\text{Generator Torque}}\qquad(3)$$

This model can be expressed using eq. (1) and (3), and it can be interpreted as a system in which the sliding parts between WT and FR mutually influence each other.

WT-DT / WT-DT-FR model

Assuming non-slip between WT and DT, the center of DT rotates by an angle ϕ around the WT axis, and considering the rotation angle θ of DT around its own axis, the angle of deviation Δ and the second derivative can be expressed as following,

$$\Delta=\phi+\frac{R_{\mathrm{DT}}}{R_{\mathrm{WT}}}\theta\quad,\qquad\frac{d^2\mathit{\Delta}}{dt^2}=\frac{d^2\phi}{dt^2}+\frac{R_{DT}}{R_{FA}}\frac{d^2\theta}{dt^2}\qquad(4)$$

Consider the rotation of WT. The 2nd term of RHS in eq. (3) is converted into the resistance torque and inertial force of DT and FR as following,

$$\underbrace{I_{\mathrm{WT}}\frac{d^2\phi}{dt^2}}_{\text{WT inertia}}=\underbrace{T_{\mathrm{WT}}}_{\text{WT torque}}+N_{\mathrm{DT}}\frac{R_{\mathrm{WT}}}{R_{\mathrm{DT}}}\left(\underbrace{T_{\mathrm{reg}}}_{\text{Generator Torque}}-\underbrace{I_{\mathrm{DT}}\frac{d^2\theta}{dt^2}}_{\text{DT inertia}}+\frac{1}{N_{\mathrm{DT}}}\frac{R_{\mathrm{DT}}}{r_{\mathrm{DT}}}\underbrace{I_{\mathrm{FR}}\frac{d^2\Delta}{dt^2}}_{\text{FR inertia}}\right)\qquad(5)$$

Consider the rotation of DT. The mooring tension at the DT axis center is adjusted by the arm length. Since DT and WT do not slip, this force generates a rotational torque with the DT radius as the arm length. The EOM for DT is as following,

$$\underbrace{I_{\mathrm{DT}}\frac{d^2\theta}{dt^2}}_{\text{DT inertia}}=\underbrace{T_{\mathrm{reg}}}_{\text{DT damping}}+\frac{1}{N_{\mathrm{DT}}}\frac{R_{\mathrm{DT}}}{r_{\mathrm{DT}}}\left(\underbrace{r_{\mathrm{Moor}}\sum_{i=1}^{N_{\mathrm{Moor}}}F_{\mathrm{Moor}\mathit{\Delta},i}}_{\text{Restoring torque by mooring line}}-\underbrace{I_{\mathrm{FR}}\frac{d^2\Delta}{dt^2}}_{\text{FR inertia}}\right)\qquad(6)$$

In WT-DT model, we can ignore FR inertia term in eq.(4)-(6).

Simulation Results

Simulation has been examined to check the validity of the PTO dynamics model with a 20 kW FAWT in a 40 m depth environment, assuming it is upright and connected by three static catenary mooring lines which consist of a combination of synthetic fiber ropes and chains. The EOMs for the rotating bodies are numerically integrated using the Euler method with a sufficiently stable time step.

As turbine torque increased, the angles, angular velocities, and accelerations of the rotating bodies showed a delay of about 100 seconds. The deviation angle Δ was approximately 16 degrees for the WT-FR model and 19 degrees for the WT-DT-FR model, indicating that the DT presence increases Δ. No significant differences were found between the WT-DT and WT-DT-FR models regarding the FR's inertial moment, likely due to the resistance torque T_{reg} being greater than the FR's inertial forces. However, the FR's inertial moment could vary with design, making it an important factor.

FAWT parameters

Pr(W)	24600
$loss_{arm}$	0.1
$loss_{sheer}$	0.05
$loss_{eff}$	0.05
P_{shaft}(W)	30464
TFA(Nm)	3714

Mooring line parameters

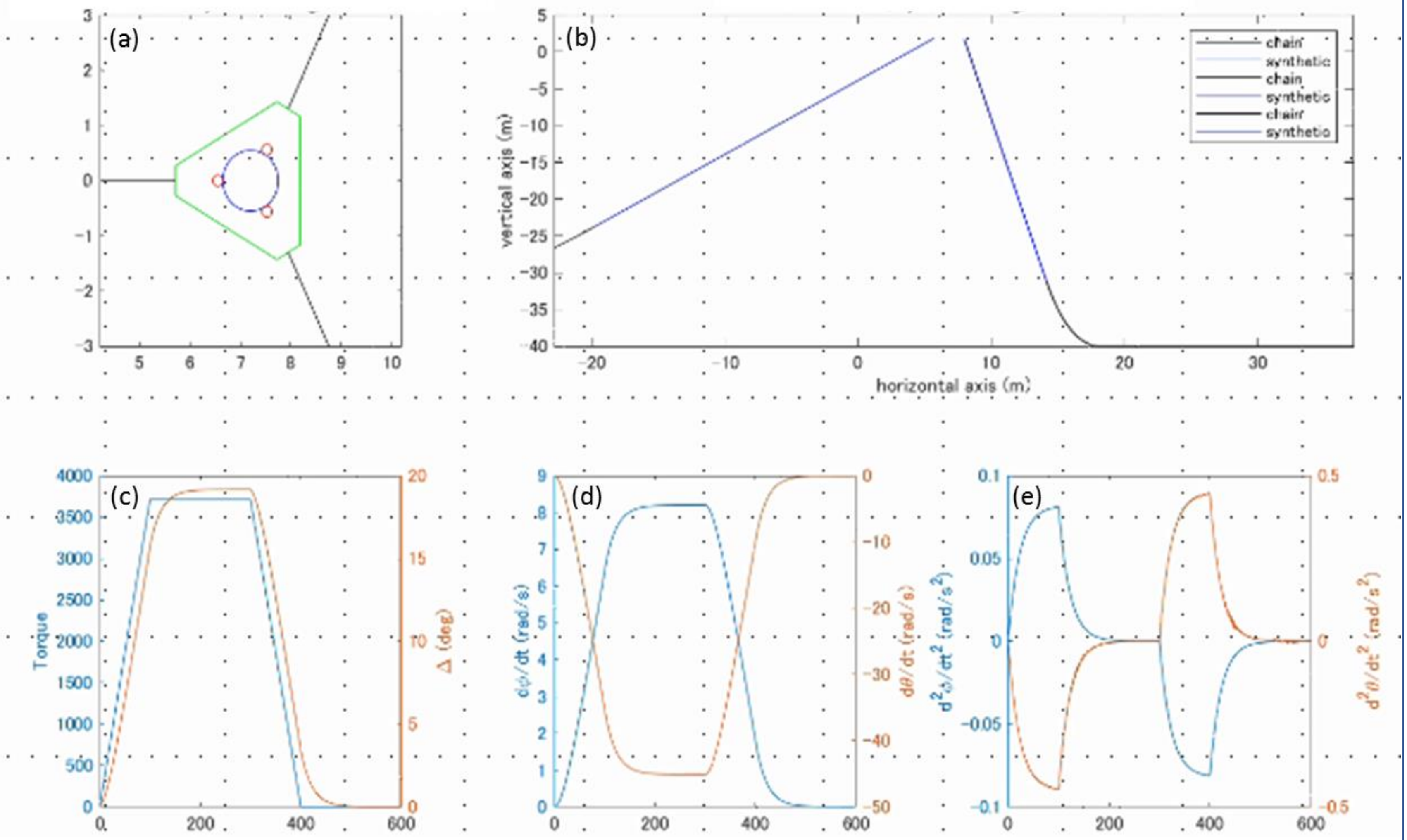
line $density_{chain,air}$ (kg/m)	19.9
d_chain (m)	0.0573
Echain(GPa)	107.065
EA(N)	2.76E+08
depth(m)	40
length(m)	103.6
Cb	1
N	3

PTO dynamics parameters

	FA−FR	FA−DT	FA−DT−FR
ζ,ζ_θ (Nm/(m/s))	452.8※1	4.990※2	4.990※2

PTO structure parameters

	FA	PTO	DT
R	0.55	1.5(rmoor)	0.1
Ixx,Iyy(kg m^2)	nan	nan	nan
Izz(kg m^2)	8200	357	20



Example of simulation results with FA-DT-FR model. (a)(b) PTO and mooring lines config., (c)-(e) time series of torque and FR angle, WT and DT rotation speeds and acceleration.

Future plan

Development of the models and simulator to investigate the control system and detailed yaw rotational behavior.

References

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