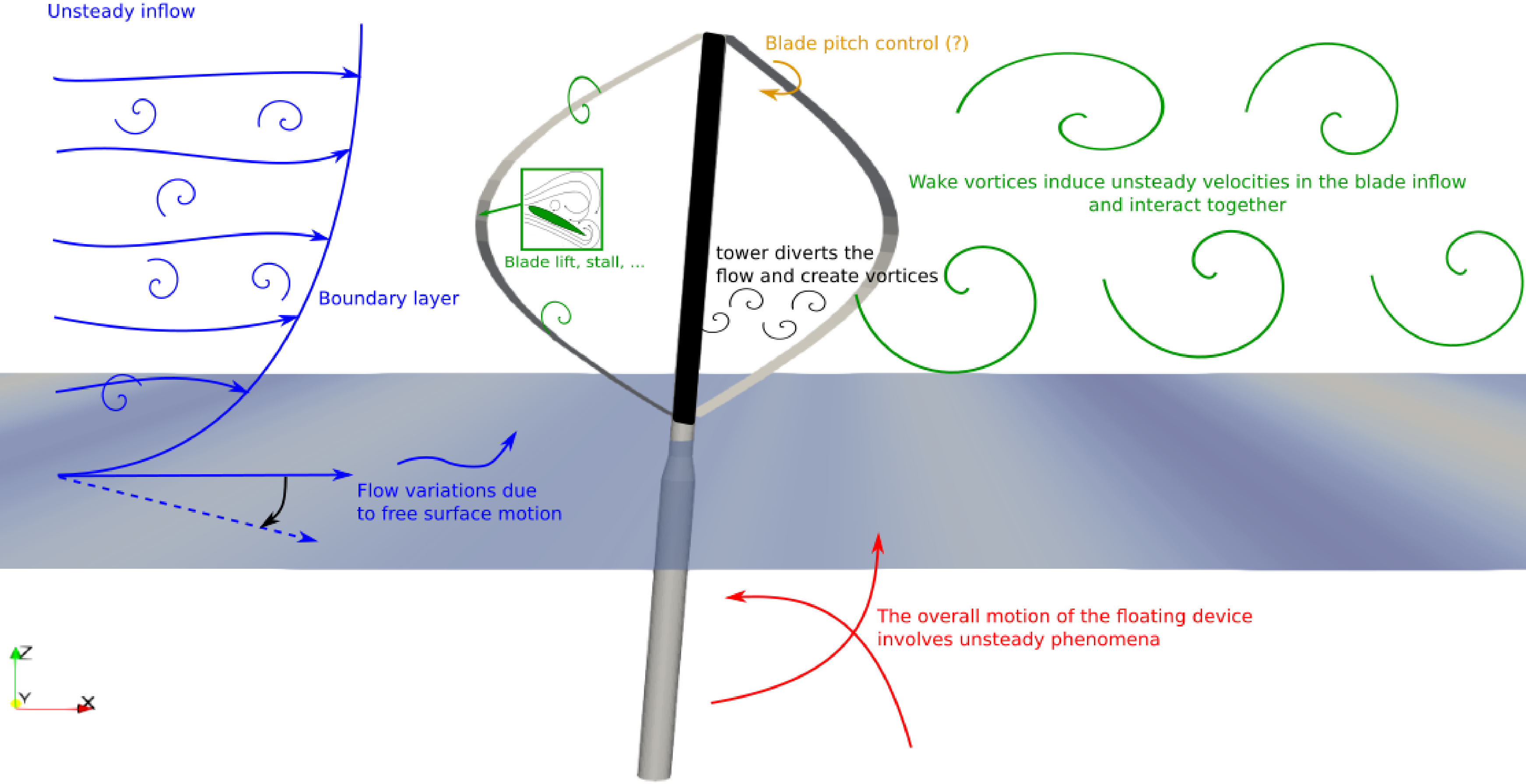
Impact of the aerodynamic model on the modelling of the behaviour of a Floating Vertical Axis Wind Turbine

Vincent LEROY[1, 2]
PhD Student

J.-C. GILLOTEAUX[1], A. COMBOURIEU[2], A. BABARIT[1], P. FERRANT[1]

[1]**LHEEA – Centrale Nantes** – 1, rue de la Noë – 44321 Nantes - FRANCE
[2]**INNOSEA** – 1 rue de la Noë – 44321 Nantes - FRANCE

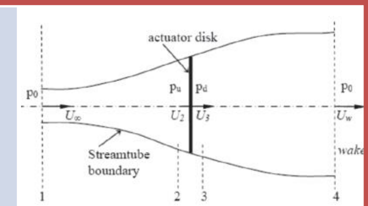
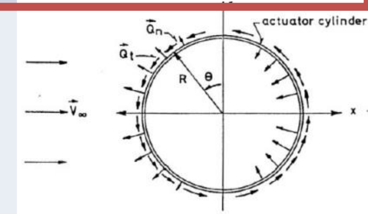
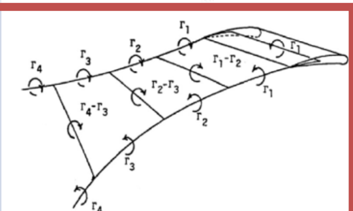
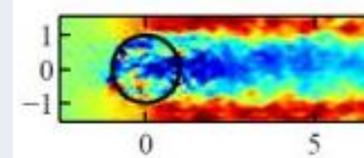
Unsteady aerodynamics of a VAWT at sea



DeepWind VAWT (Paulsen et al., 2014)

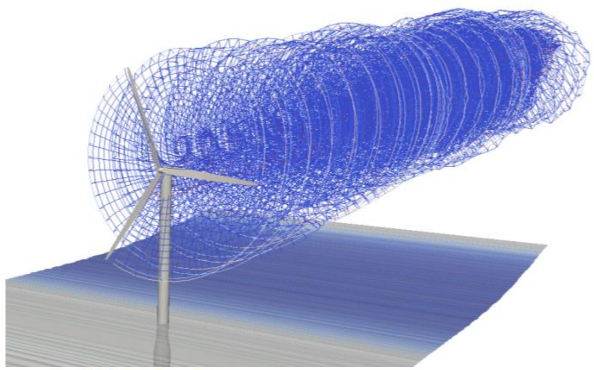
Aerodynamic modelling of VAWTs

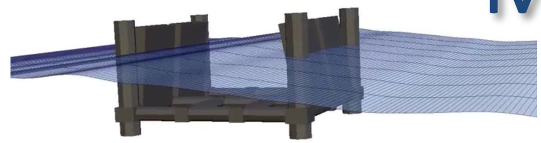
- Amongst other theories…
  - Inviscid models can usually account for viscous effects with **semi empirical models**

	Assumptions	Pros	Cons	
DMS [1] *Double Multiple Streamtube*	**Steady** Inviscid flow Actuator disks	Fast State-of-the-art	Steady **Problems at high TSRs**	
AC [2] *Actuator Cylinder*	Steady, 2D, Inviscid, Incompressible flow	Fast Accurate cylindrical swept surface Viscous models added	Steady flow Difficult to go 3D	
FVW [3] *Free Vortex Wake + lifting line theory*	Potential flow Lifting line	**Unsteady** aerodynamics Inherent rotor/wake and wake/wake interactions	High CPU cost	
CFD *Actuator line + RANS* *LES, …*	*Var*		Very high CPU cost	

Which model can we use for a FVAWT ?

[1] (Paraschivoiu, 2002) [2] (Madsen, 1982) [3] (Murray et al., 2011)





Modular coupling

InWave by INNOSEA

Including ***NEMOH***
(Babarit et al., 2015)

Moorings
MAP++

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Hydrodynamics and multi-body solver

Positions/velocities of blade elements

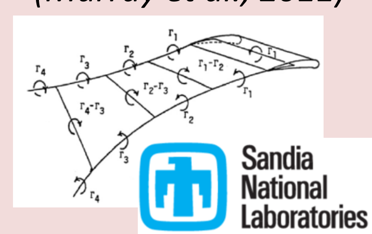
Forces and moments on the rotor

Wind
constant/turbulent

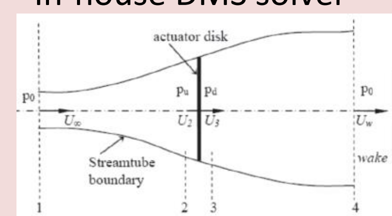
Rotor geometry

Aerodynamic solver FVW / DMS

CACTUS *(SNL)*
(Murray et al., 2011)



In-house DMS solver



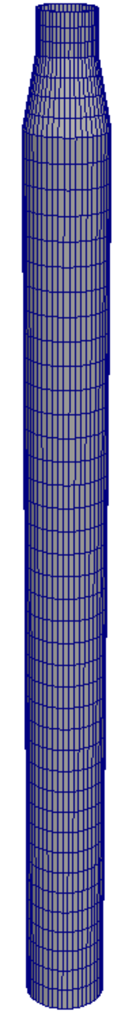
Skew correction (Wang, 2015)
Dynamic stall

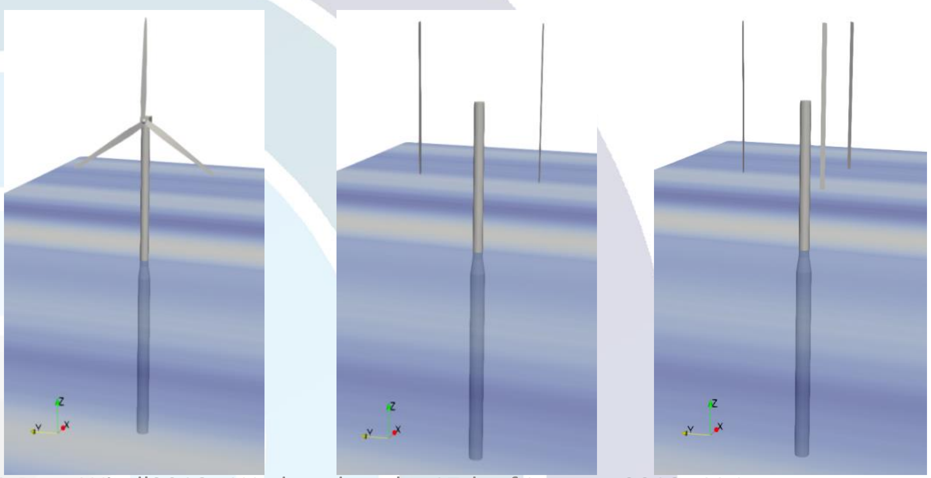
Control

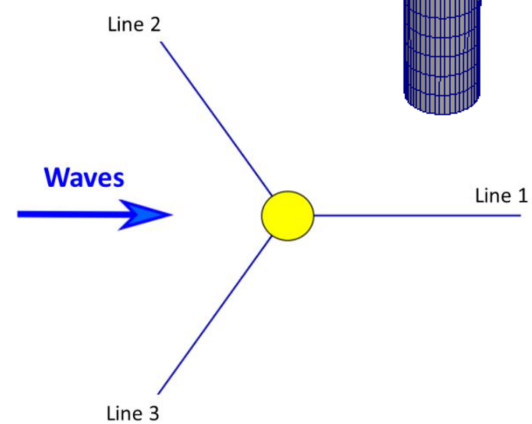
A control module dedicated to **floating VAWTs** (Merz et al., 2013) and adapted as (Cheng, 2016) for our study, filtering $n * p$ frequencies.
Or other DLL

Studied Floating HAWT and VAWTs

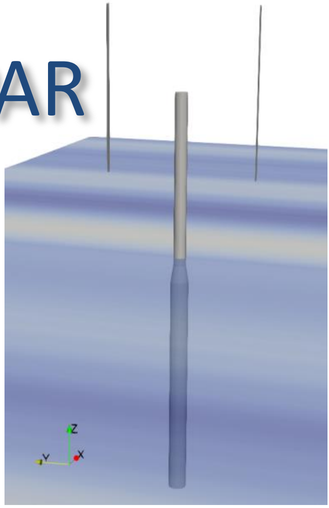
- **NREL 5MW HAWT** on the **OC3Hywind SPAR** (Jonkman, 2010)
- **2 and 3 bladed H-VAWTs of equal solidity**, on the **OC3Hywind SPAR**
  - Designed by (Cheng, 2016)
- Same mooring system, with an **added linear spring acting in Yaw** (Jonkman, 2010)
- **<u>Rigid</u> bodies (SPAR, tower and blades)**
- **Studied:**
  - Motion RAOs with **"white noise" waves and constant wind (DMS vs. FVW)**
  - OC3 load cases in time domain for the VAWTs with **DMS vs. FVW** solvers
    - **H2 presented today**







OC3 load cases on the H2 + OC3Hywind SPAR

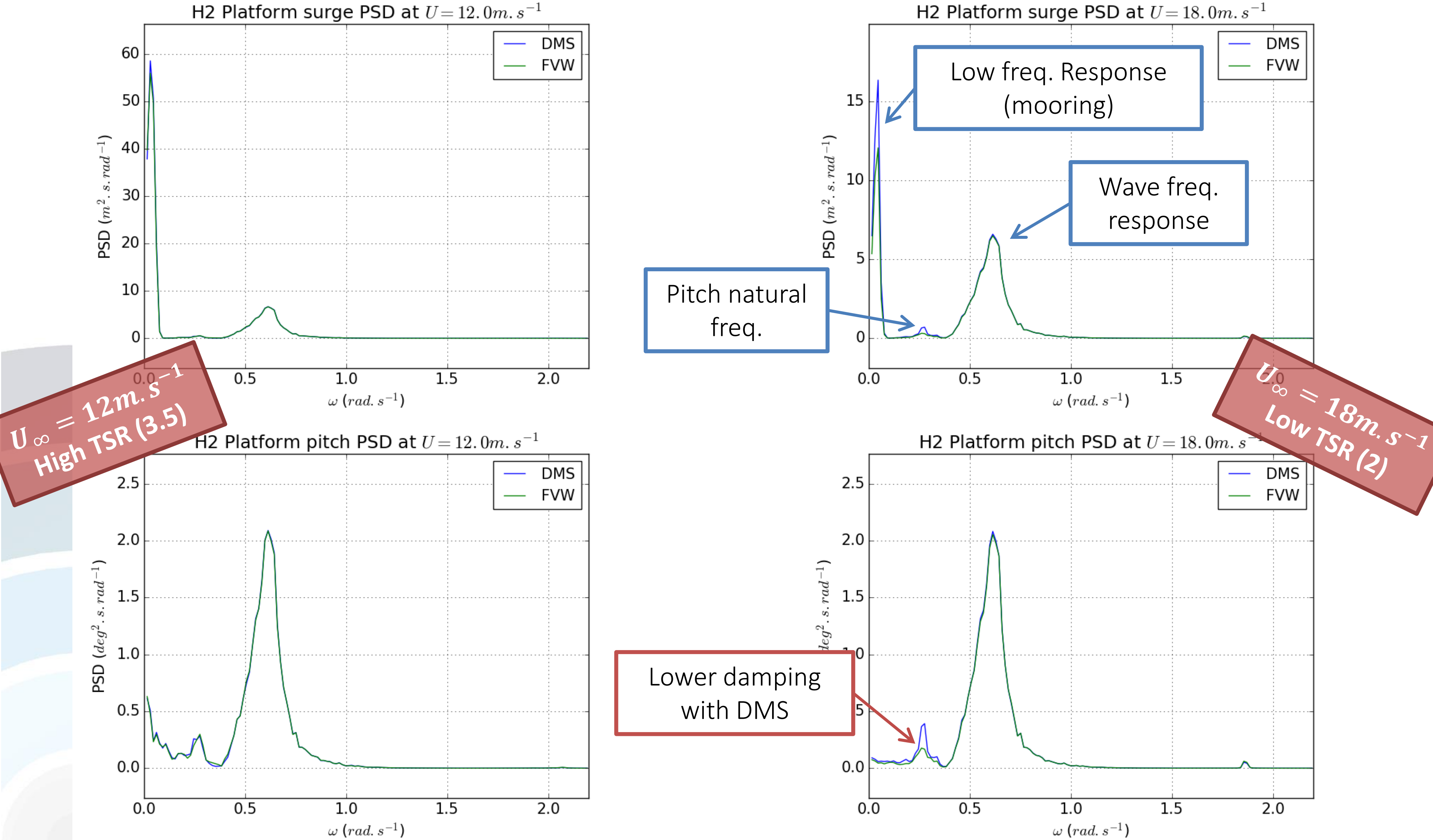


- Environmental conditions
  - $T_p = 10s$, $H_s = 6m$
  - Kaimal spectrum wind (x, y, t)
    - $U_\infty = 12m.s^{-1} \rightarrow TSR \approx 3.5$
    - $U_\infty = 18m.s^{-1} \rightarrow TSR \approx 2$

- Simulations run on $5000s$
  - Transient regime removed for analysis

- Relevant output data
  - Platform motions 6 DOFs
  - Aerodynamic loads and power on the rotor (F_x, F_y, P)
  - Aerodynamic loads on an equatorial blade element F_N, F_T

Power Spectral Densities: platform motions



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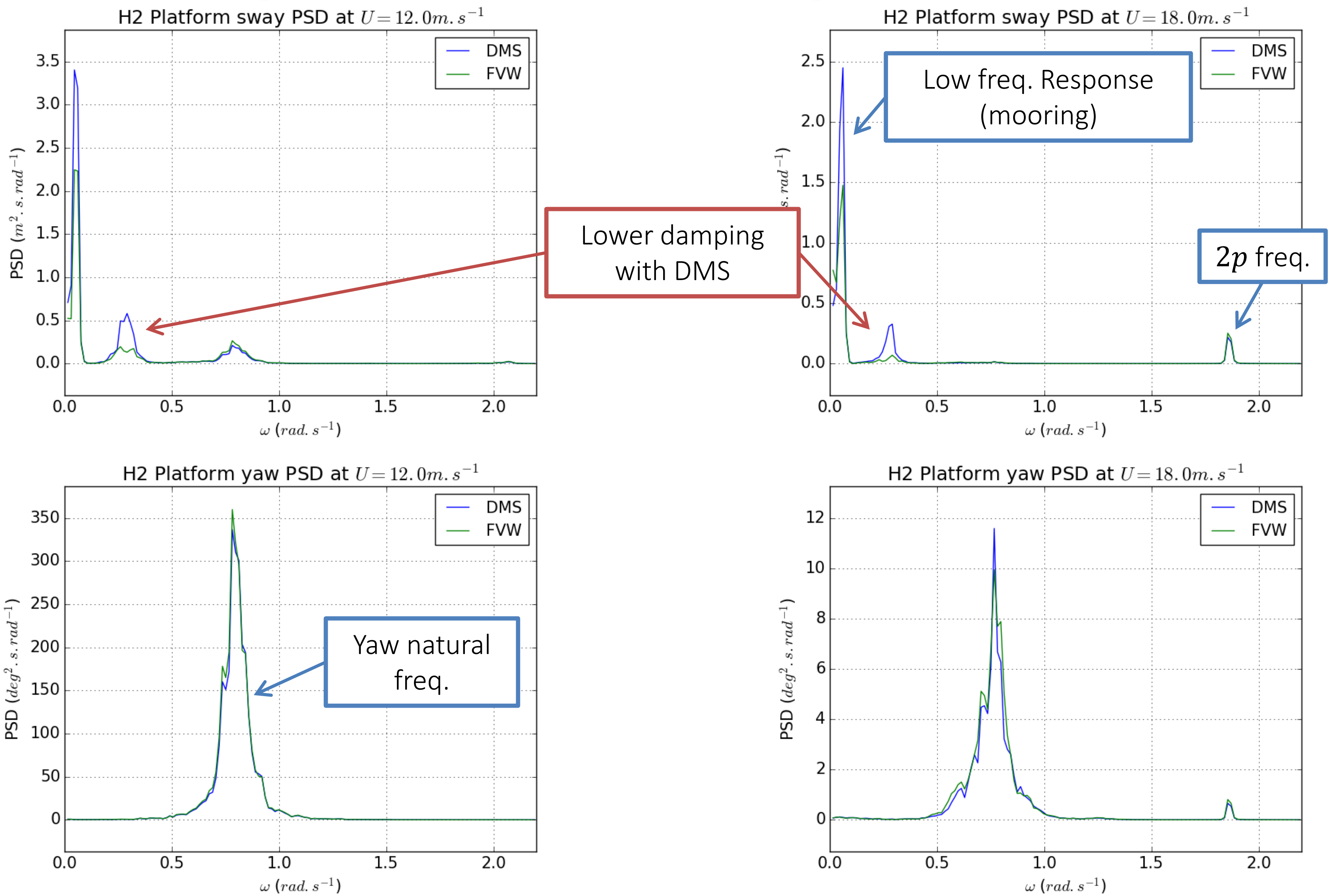
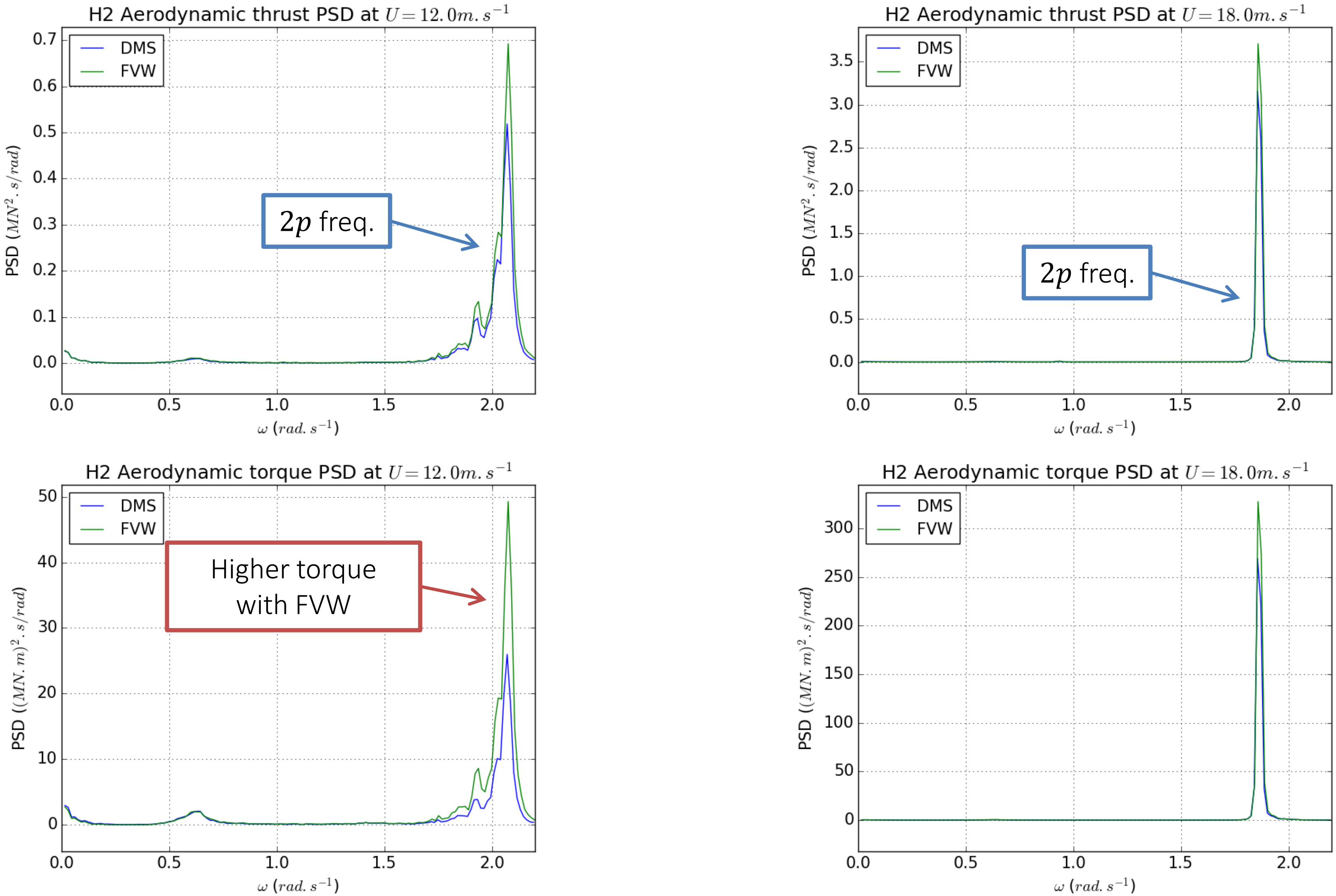
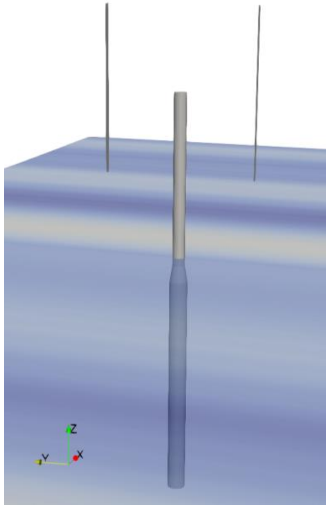


Power Spectral Densities: aerodynamic loads



Power Spectral Densities: conclusions

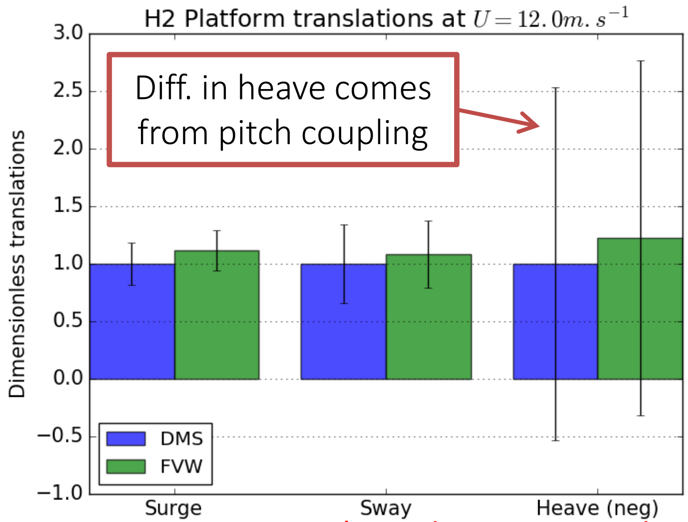
- Similar motion PSDs in response to the two models: DMS and FVW
  - Surge, Heave, Pitch
  - Yaw (at natural frequency)
  - At waves and low frequencies

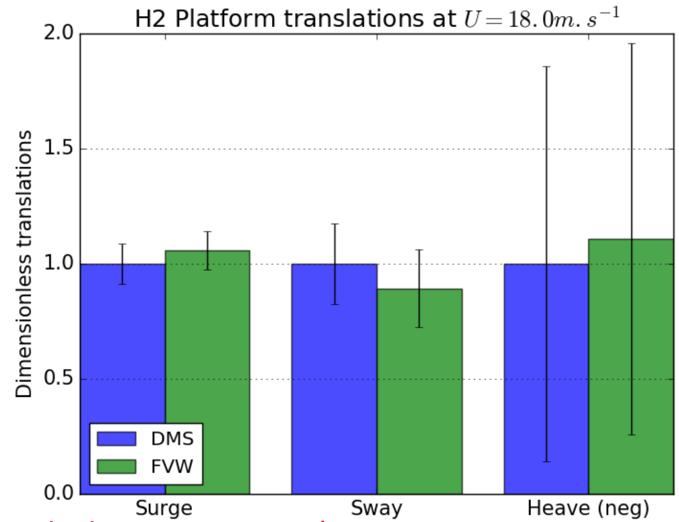


- Higher damping on the transversal motions with FVW
  - Differences in sway and roll at natural frequencies

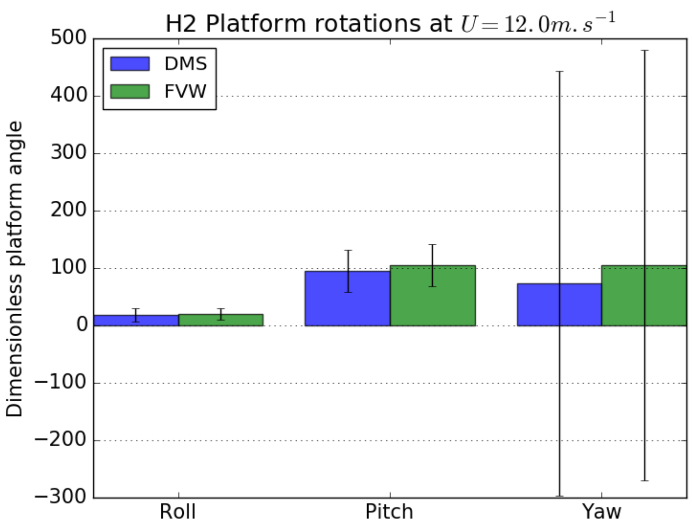
- Important differences at high TSRs for the torque PSDs
  - At the $2p$ frequency
  - Similar behaviour at low frequencies

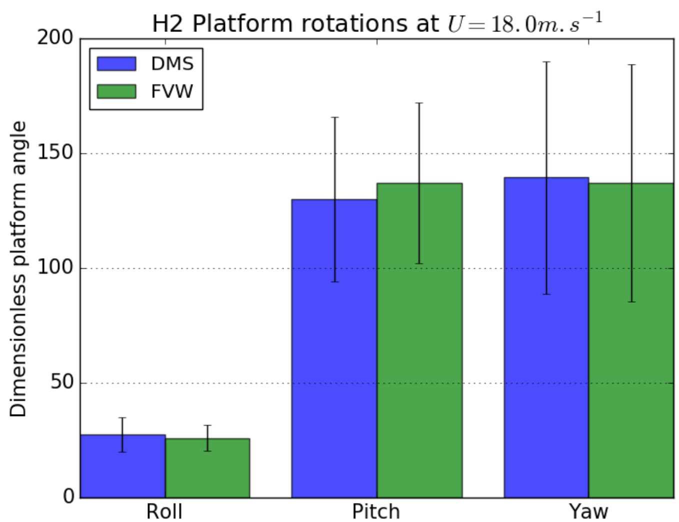
Mean and std: platform motions





(Translations normalised with the DMS output)



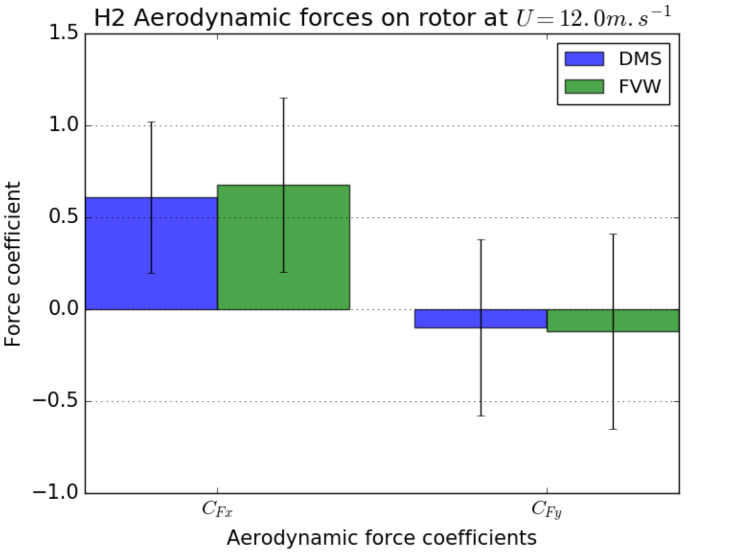


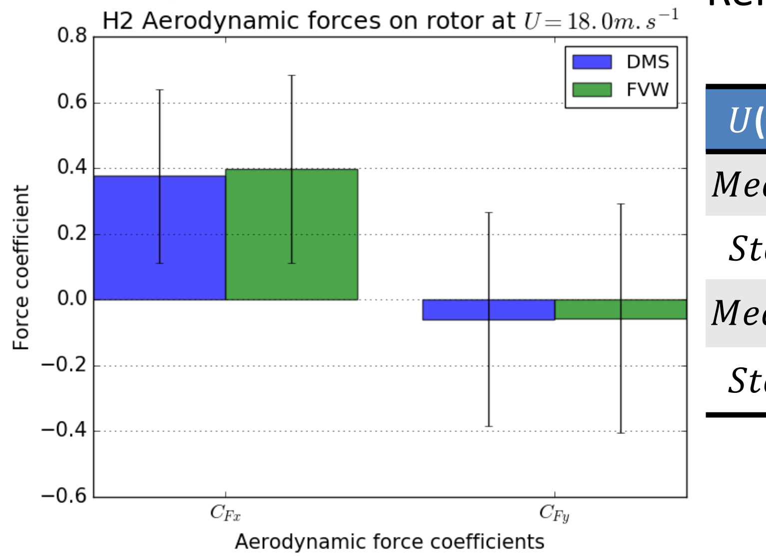
Relative differences: DMS vs. FVW

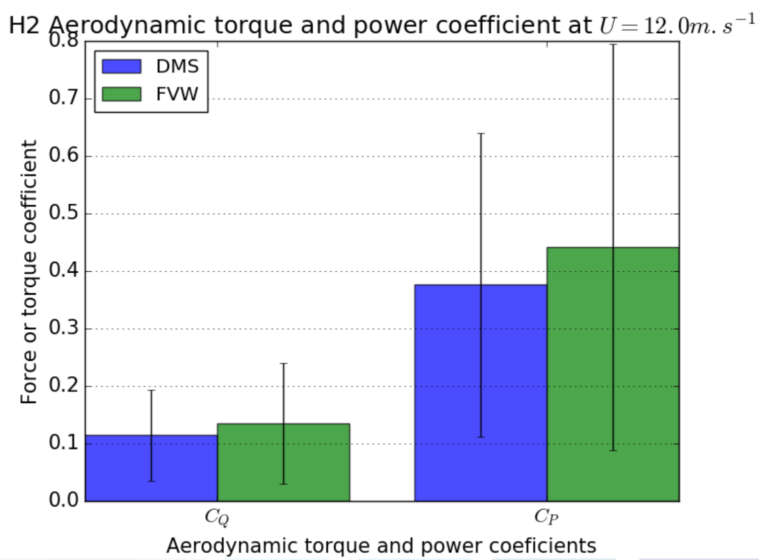
$U(m.s^{-1})$	12	18
$Mean(X)$	12%	6%
$Std(X)$	1%	6%
$Mean(Y)$	9%	11%
$Std(Y)$	14%	3%

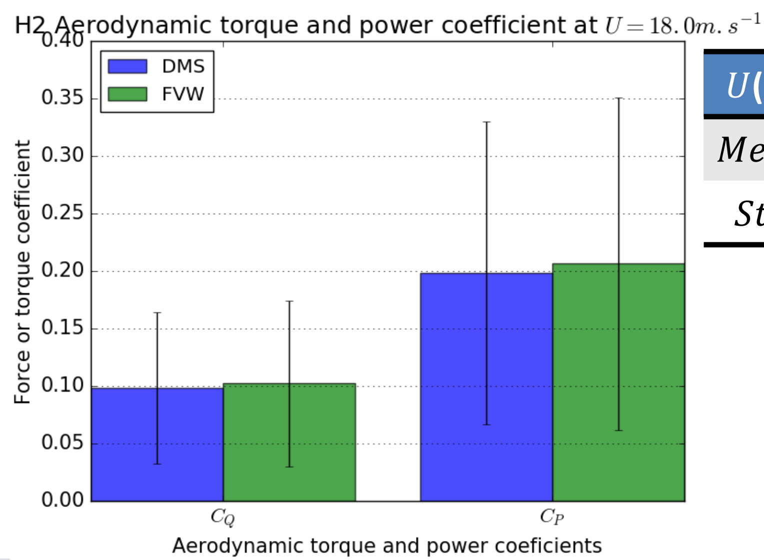
$U(m.s^{-1})$	12	18
$Mean(\varphi)$	13%	6%
$Std(\varphi)$	14%	24%
$Mean(\theta)$	10%	5%
$Std(\theta)$	0%	2%
$Mean(\psi)$	19%	4%
$Std(\psi)$	1%	2%

Mean and std: aerodynamics









Relative differences:
DMS vs. FVW

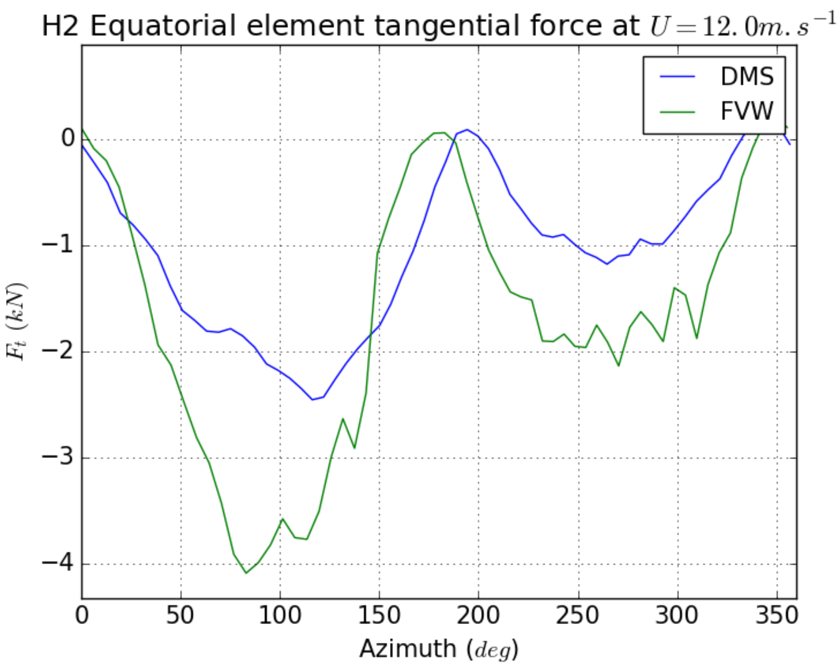
$U(m.s^{-1})$	12	18
$Mean(C_{Fx})$	12%	6%
$Std(C_{Fx})$	15%	9%
$Mean(C_{Fy})$	19%	5%
$Std(C_{Fy})$	11%	8%

$U(m.s^{-1})$	12	18
$Mean(C_P)$	17%	4%
$Std(C_P)$	33%	10%

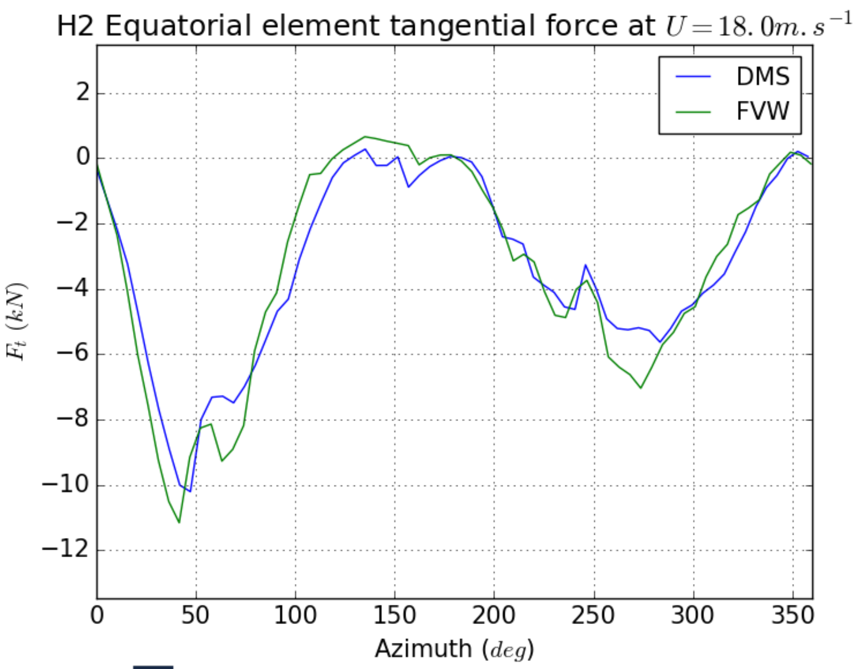
Loads on a blade element

- Tangential load on equatorial blade element on a revolution
  - 25% relative difference on **mean load** at $12m.s^{-1}$
  - 37% relative difference on **std** at $12m.s^{-1}$
- Impact if considering flexible blades ?

$TSR = 3.5$



$TSR = 2$



Conclusions

- On this case, with the OC3Hywind SPAR platform:
- Impact of the aerodynamic model on the H2 (OC3 load case): **DMS vs. FVW**
  - **No substantial effect on PSDs** (except transversal motions)
  - *Same conclusion on the motion RAOs with wind*

- Difficult to process mooring line tensions with this mooring model
  - Added linear stiffness in yaw, designed for a HAWT
  - A more detailed model could be important

- When focusing on mean and std:
  - At low TSR: models behave similarly
  - At high TSR: important differences on mean and std for
    - Aerodynamic loads
    - Motions

→ **DMS seems to miss important aerodynamic unsteady effects due to strong rotor/wake interactions at high TSR**

→ It could have a **strong impact** when looking at **blade design** (with **flexible blades**), for instance

- **Similar conclusions are obtained with the H3 VAWT** on the same load cases (not presented here…)
  - Comparative study to come

References

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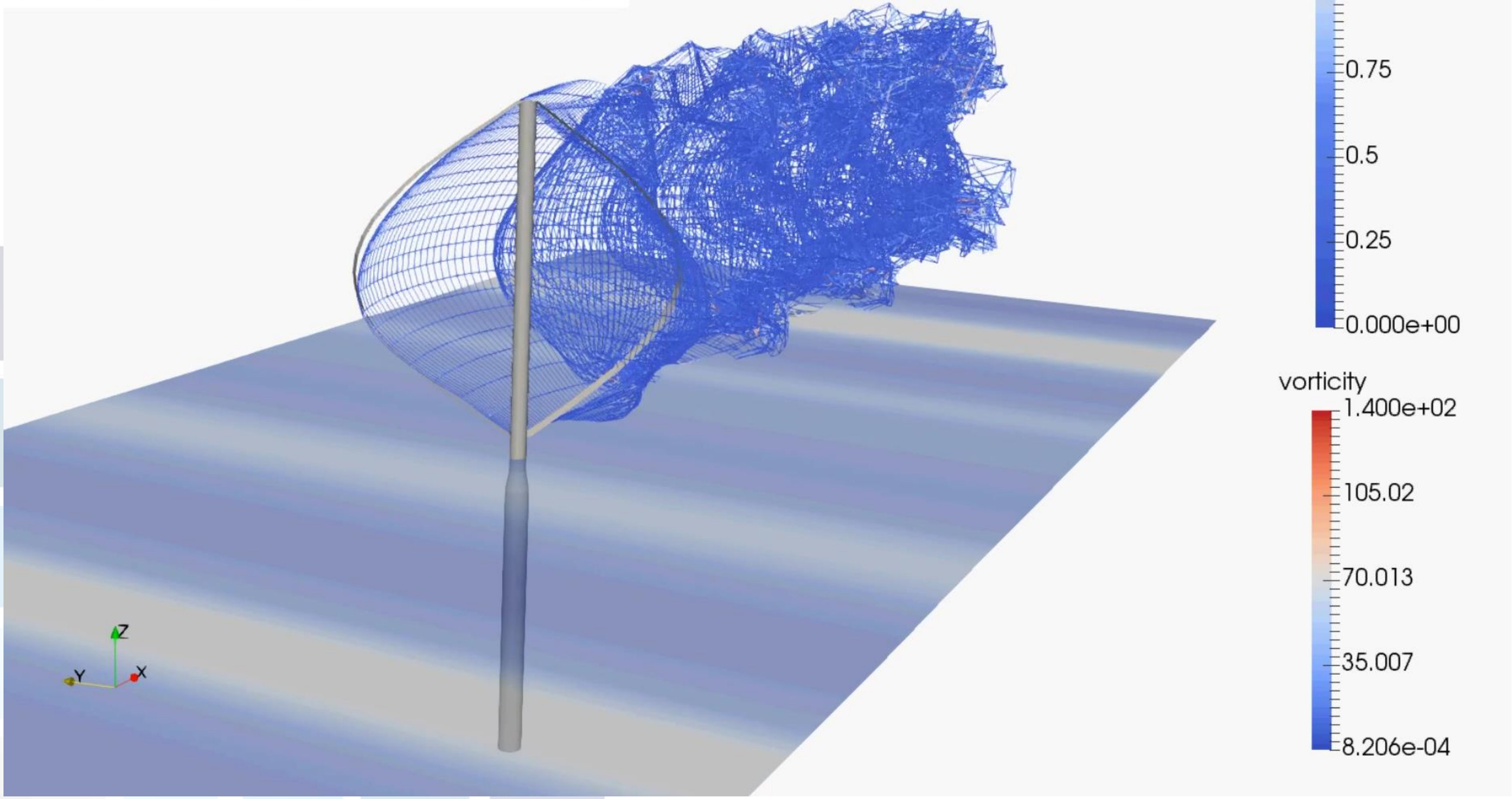
Takk !

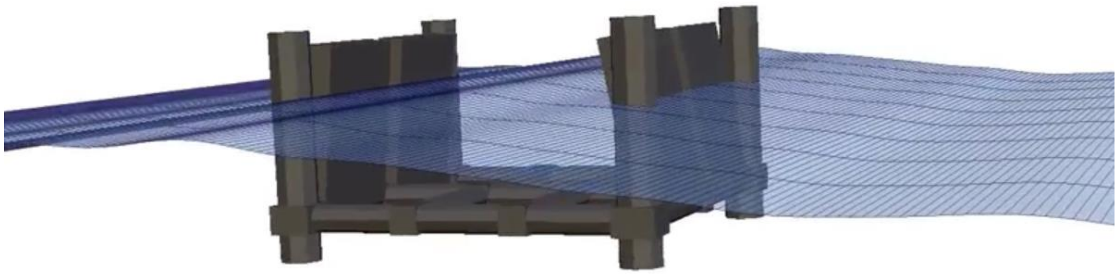
Contact: vincent.leroy@ec-nantes.fr



Coupled simulation tool: seakeeping

- *InWave* is developed at INNOSEA in collaboration with LHEEA Lab. of Centrale Nantes

- Key features:
  - Hydrodynamics: linear potential flow solver Nemoh (developed at Centrale Nantes)
  - Mechanics: multi-body solver
  - Quasi-steady mooring model (MAP++)
  - Accounts for Power Take Off (generator) and control laws (blade pitch and/or generator)
  - Solves the equations of motion in time domain using RK4 or Adams-Moulton scheme
  - Considers regular or irregular waves



Coupled simulation tool: FVW solver

- CACTUS
  - **C**ode for **A**xial and **C**ross-flow **TU**rbine **S**imulation
  - Developed at Sandia National Laboratories (BSD License)

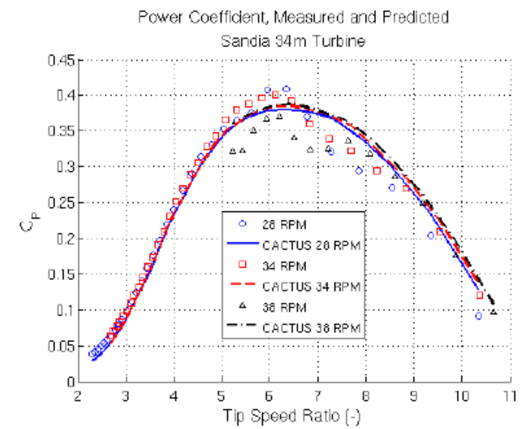
- **Free Vortex Wake** theory – **lifting line** theory
  - Potential flow, unsteady
  - Either HAWT or VAWT
  - Works with known profiles (C_d, C_l, C_m)
  - Inherently accounts for tip vortices, rotor/wake interactions, skewed inflow

- Computes:
  - Unsteady aerodynamic loads, including the tower shadow
  - Including dynamic stall models:
    - Boeing-Vertol
    - Leishman-Beddoes
  - Pitch rate and added mass effects

- **Validated** on fixed **horizontal** and **vertical rotors**

- Added:
  - Parallel computing, turbulent inflow, visualizations, platform motions

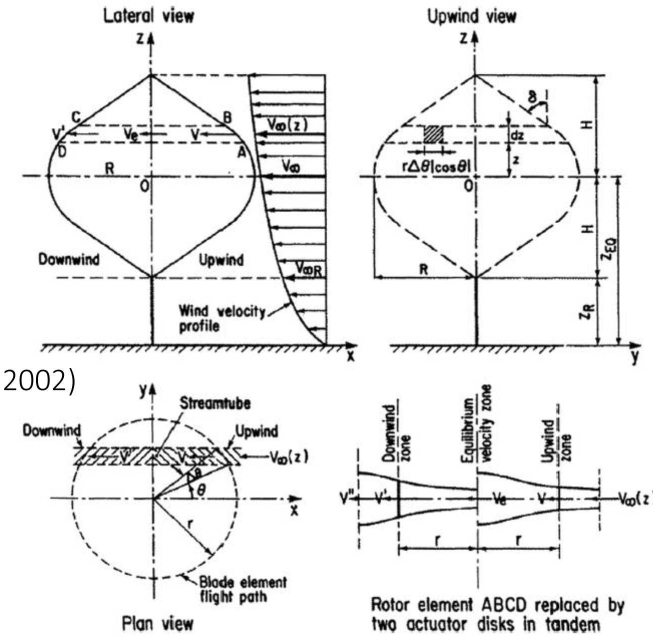
SNL 34 m VAWT



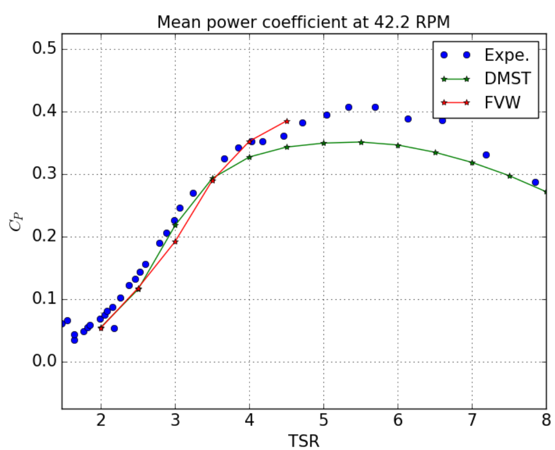
(Murray et al., 2011)

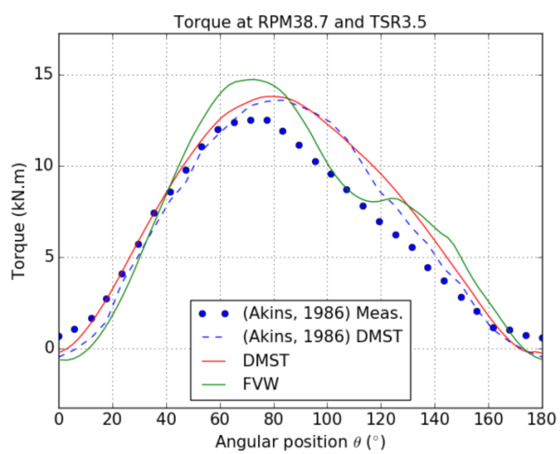
Coupled simulation tool: DMS solver

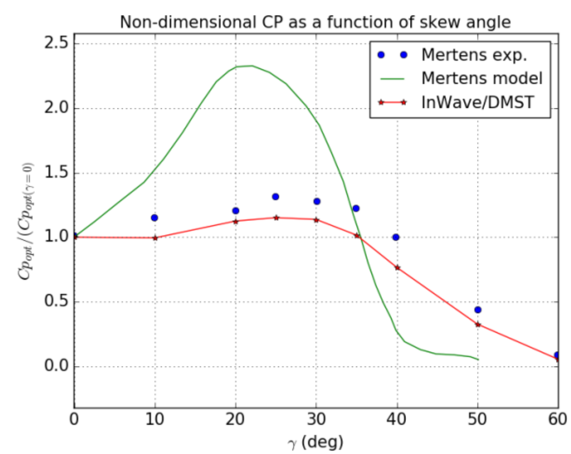
- Theory from Paraschivoiu (2002)
  - Assumes steady and potential flow
  - Large number of double streamtubes
  - With actuator disks upwind and downwind
- Added:
  - Leishman-Beddoes dynamic stall model
  - Skew model as presented in Wang (2015)
  - Validated on a fixed turbine (SANDIA 17m) (Akins, 1986)
  - And in a skewed flow (Mertens, 2003)



(Parachivoiu, 2002)

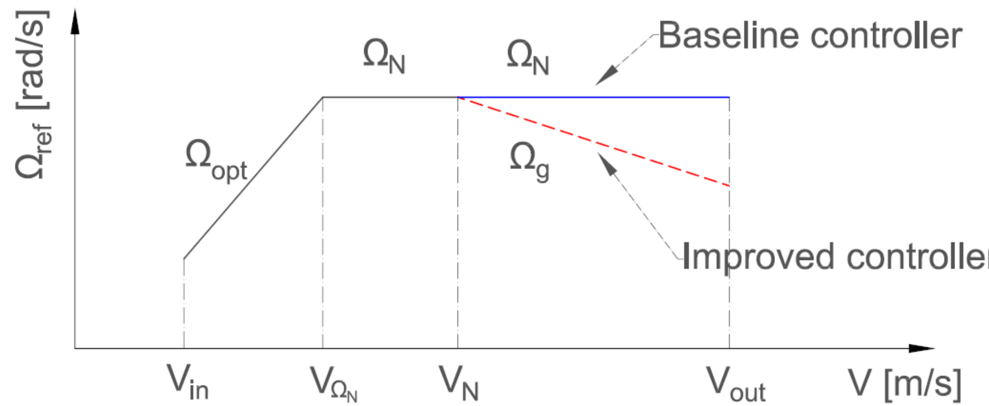




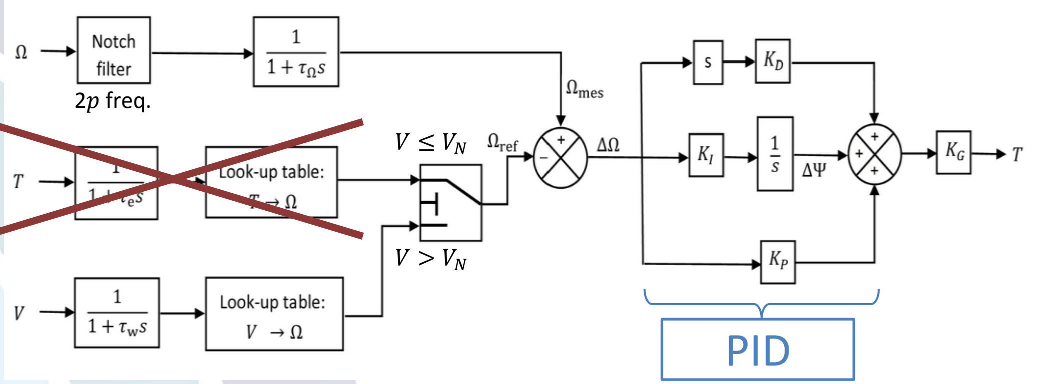


Control algorithm (Merz, 2013)

- Adapted by (Cheng, 2016)



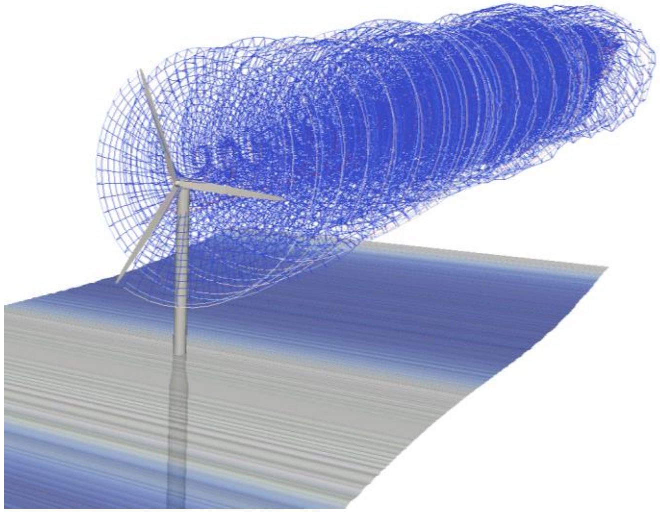
Constant power for over-rated wind speeds



(Cheng, 2016)

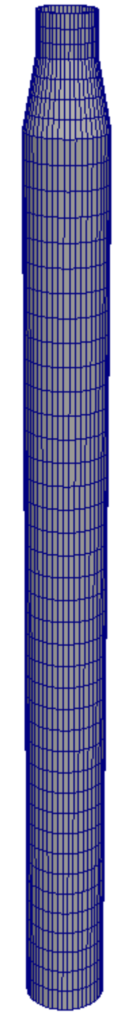
« Code-to-code » comparison

- First study on a floating HAWT with InWave + CACTUS
  - *OC3Hywind + NREL5MW (OC3)*
  - J. Jonkman et al., "Definition of the Floating System for Phase IV of OC3. Technical Report NREL/TP-500-47535", *National Renewable Energy Laboratory, National Renewable Energy Laboratory*, 2010



- Presented at OMAE2017 @Trondheim, Norway
  - V. Leroy, J.-C. Gilloteaux, M. Philippe, A. Babarit & P. Ferrant, "Development of a simulation tool coupling hydrodynamics and unsteady aerodynamics to study Floating Wind Turbines", *Proceedings of the ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering, OMAE2017, June 25-30, 2017, Trondheim, Norway*, **2017**

Studied Floating HAWT and VAWTs



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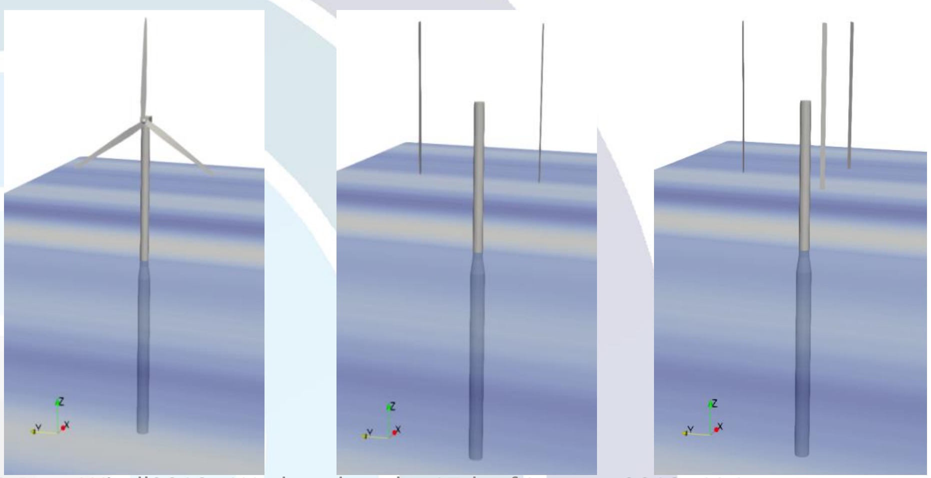
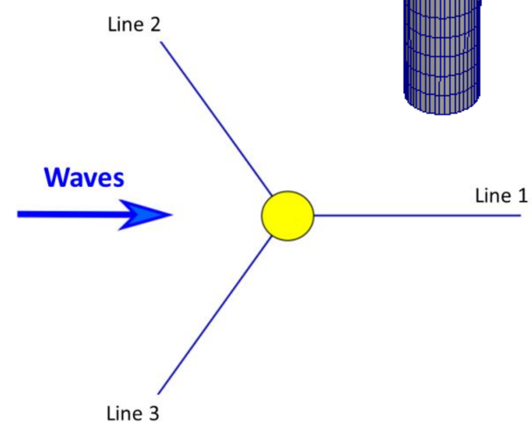
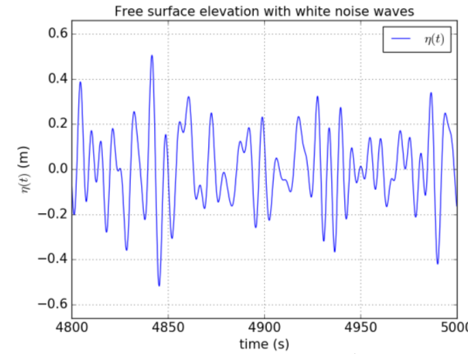
- **<u>Rigid</u> bodies (SPAR, tower and blades)**
- **Studied:**
  - Motions RAOs from **"white noise" waves and wind (DMS vs. FVW)**
  - OC3 load cases in time domain for the VAWTs with **DMS vs. FVW** solvers
    - **H2 presented today**

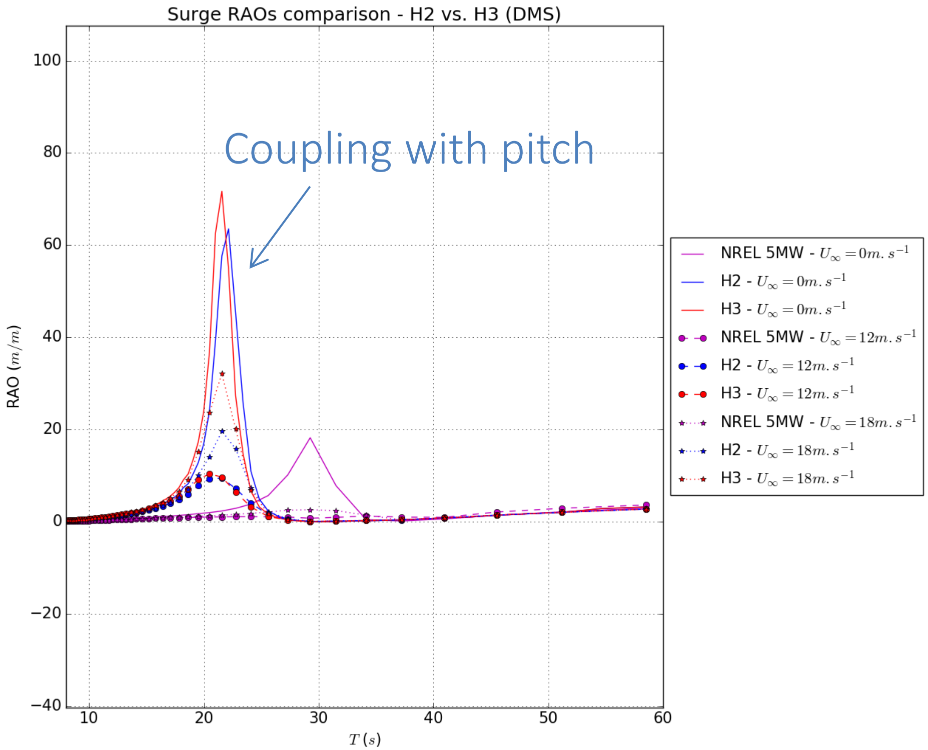


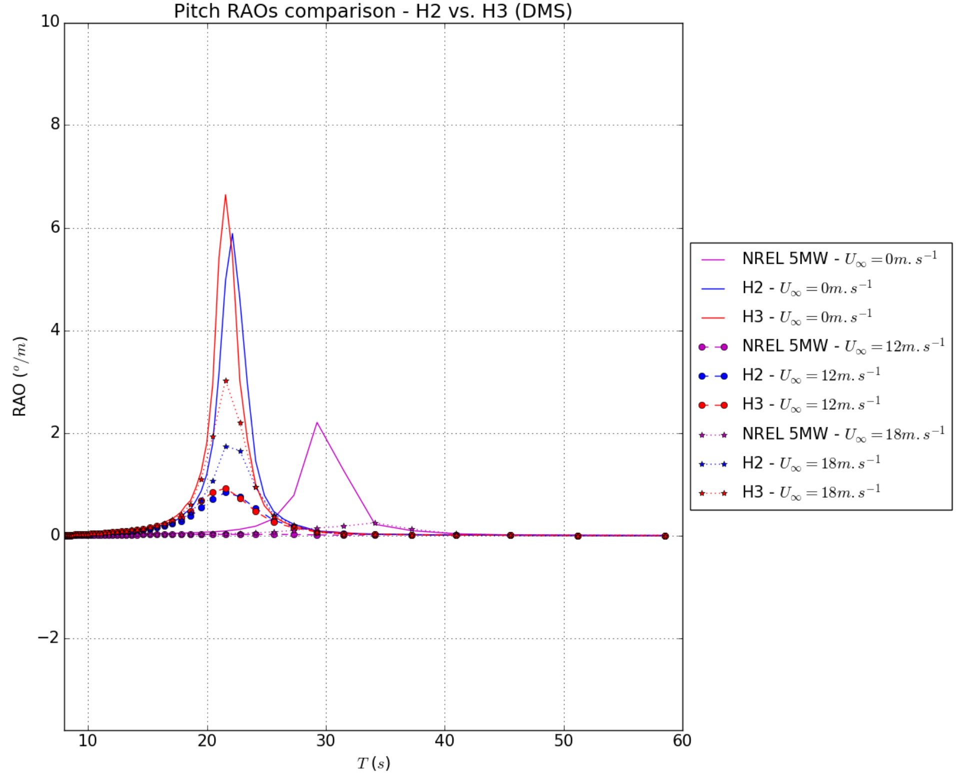


Motion RAOs from time domain



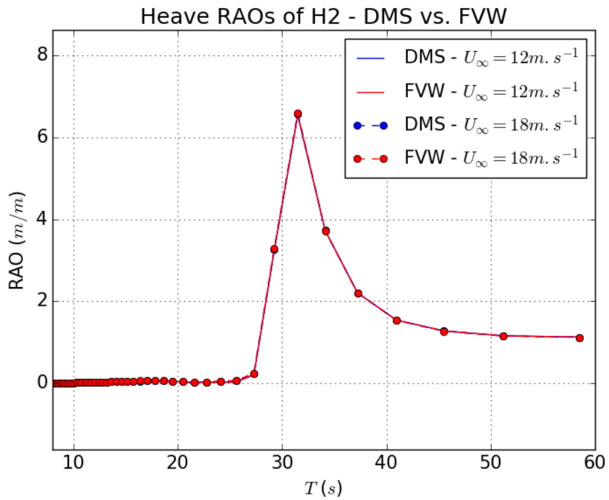
- Conditions:
  - White noise waves
  - Constant wind: $U_\infty = 0, 8, 12, 18\ m.s^{-1}$ (Only BEM (**FAST**) for HAWT or DMS for VAWTs)
- Post-processing:
  - PSD computation as in (Ramachandran et al., 2013)
  - $RAO(\omega) = \frac{S_{motion}(\omega)}{S_{waves}(\omega)}$, on the waves frequencies

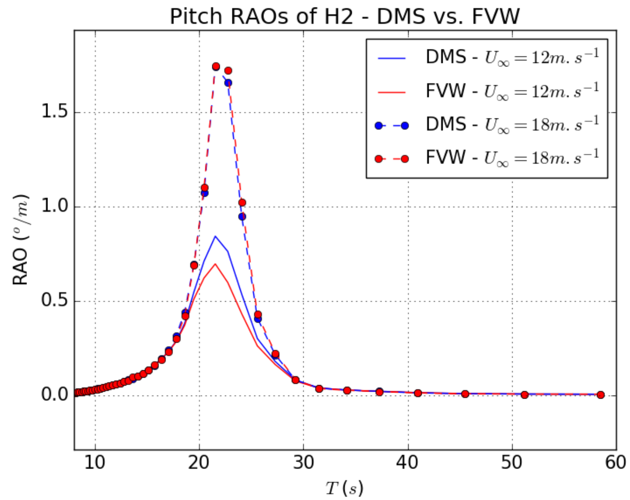




Impact of aero model and RAOs

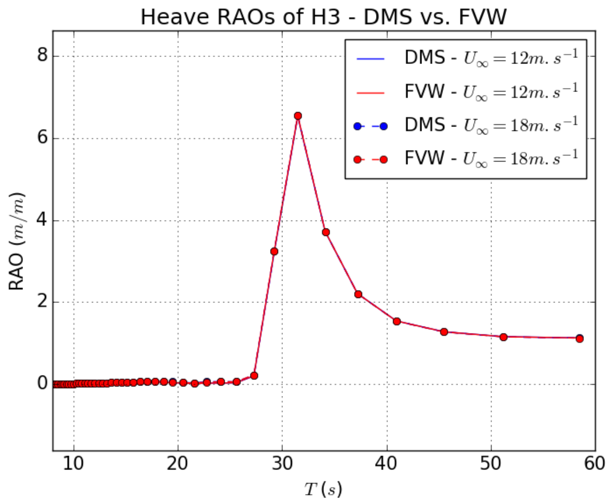
- **Comparison of these RAOs for VAWTs: DMS vs. FVW**

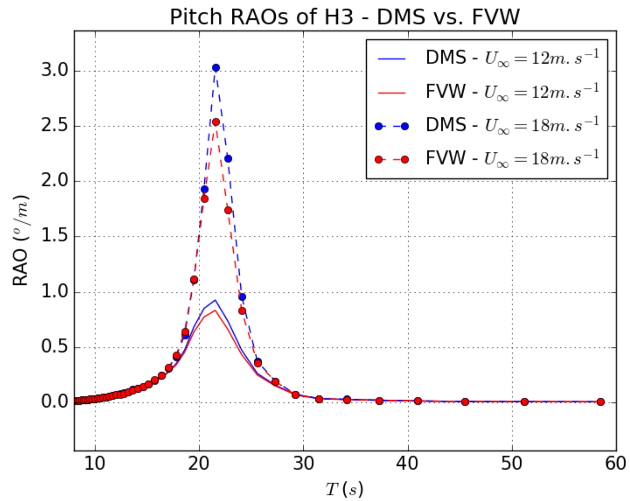




No effect on heave

Damping seems to be **more important in FVW** model





No other effect on RAOs