NOWITECH final event 22-23 August 2017

Integrated models of offshore wind turbines

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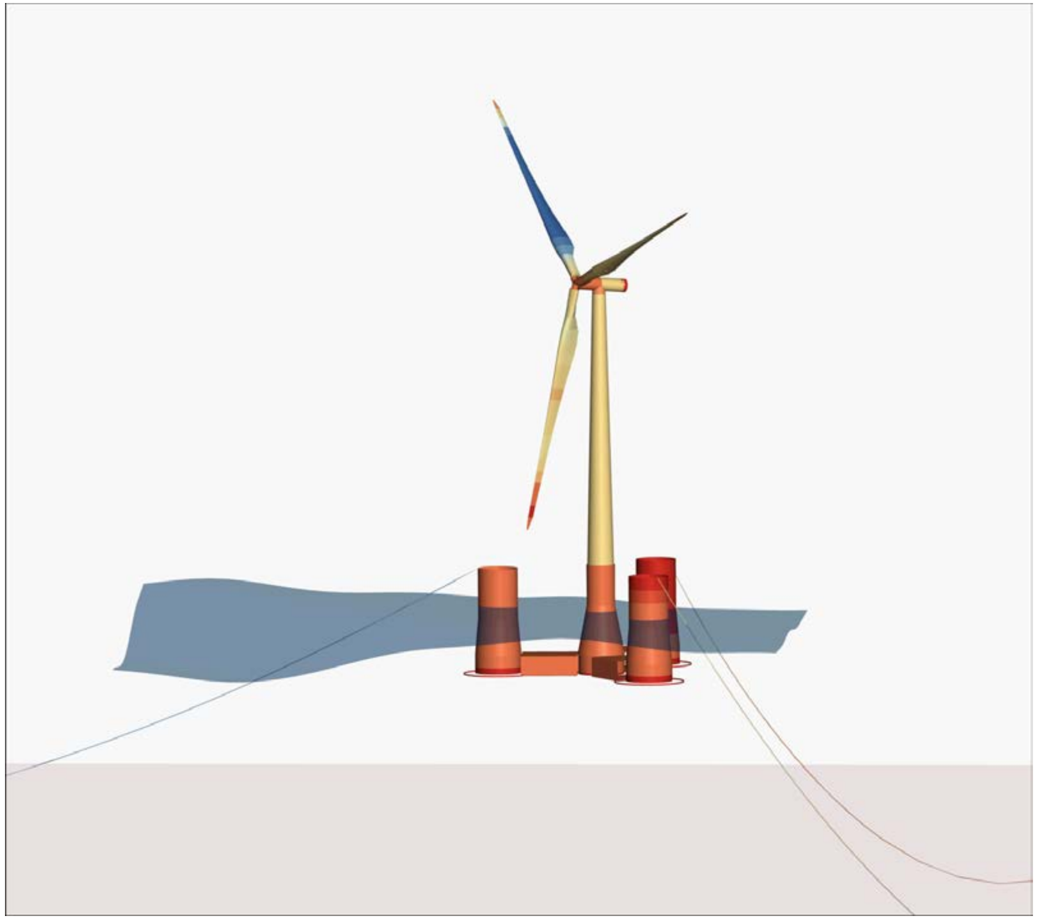
Outline

- Integrated models; what is it ?
- Where did we start eight years ago ? OC3-Hywind, IEA Code to Code Comp.
- Where are we now ? OC5 Validation against experimental data
- NOWITECH validation examples
- Is it going to pay off ?
- Unexpected, positive side effects
- What next ?

Integrated models

Stability and fatigue at rated power

Survival at ultimate limit state

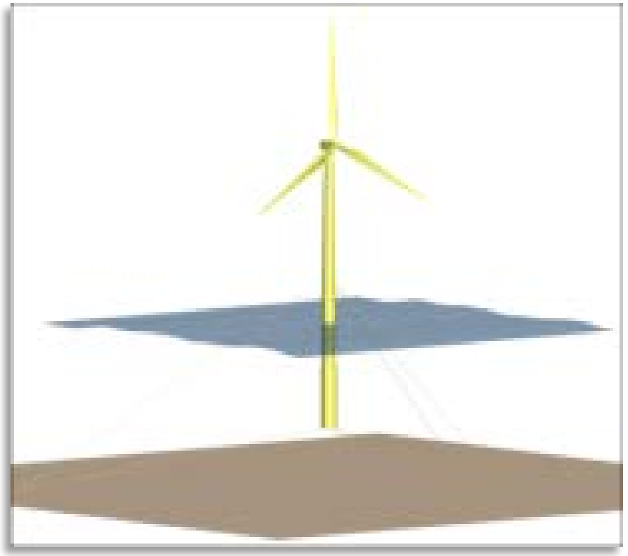


Status at NOWITECH start

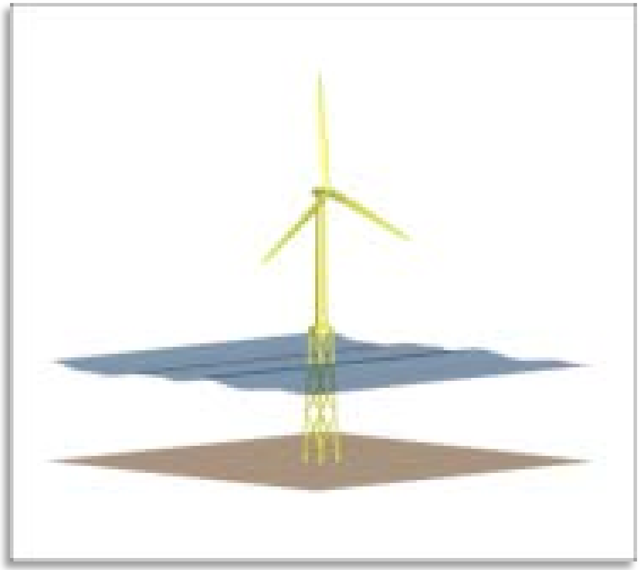
- Prior work at Hydro/Statoil: Pitch controller stability, inclusion of hydrodynamics in DTU FLEX5
- Simulations with DTU HAWC2
- Model test of HYWIND Spar-buoy at MARINTEK
- Offshore Code Comparison Collaboration within IEA Wind Task 23 (OC3)
  - Code to code comparison of simulation of different wind turbines
  - MARINTEK, IFE/NMBU and NTNU participated from 2009

Code to code verification: IEA OC3/OC4/OC5

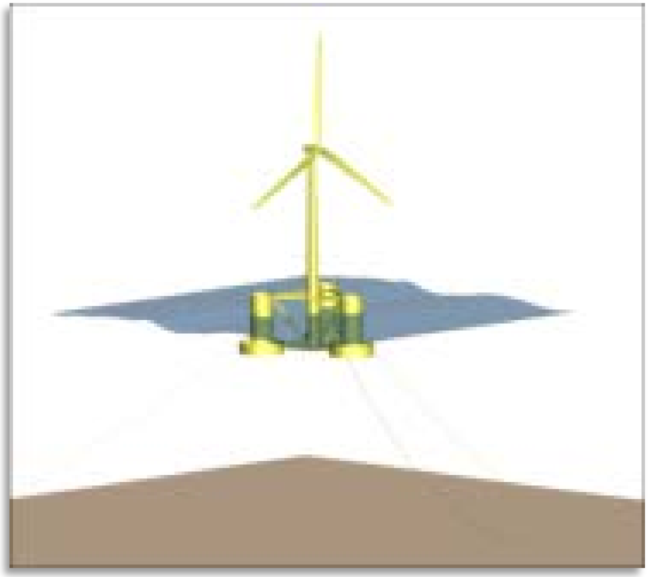
2010



2012



2014



Offshore Code Comparison Collaboration within IEA Wind Task 23:
Phase IV Results Regarding Floating Wind Turbine Modeling
Jonkman, J.; Larsen, Torben J.; Hansen, Anders Melchior; Nygaard, T.; Maus, K.; Karimirad, M.; Gao, Z.; Moan, T.; Fylling, I.; Nichols, J.; Kohlmeier, M.; Pascual Vergara, J.; Merino, D.; Shi, W.
Published in: EWEC 2010 Proceedings online

FAST	Bladed	ADAMS	HAWC2	3Dfloat	Simo	SESAM / DeepC
Code Developer						
NREL	GH	MSC + NREL + LUH	Risø-DTU	IFE-UMB	MARINTEK	DNV
OC3 Participant						
NREL + POSTECH	GH	NREL + LUH	Risø-DTU	IFE-UMB	MARINTEK	Acciona + NTNU
Aerodynamics						
(BEM or GDW) + DS	(BEM or GDW) + DS	(BEM or GDW) + DS	(BEM or GDW) + DS	(BEM or GDW)	BEM	None
Hydrodynamics						
Airy+ + ME, Airy + PF + ME	(Airy+ or Stream) + ME	Airy+ + ME, Airy + PF + ME	Airy + ME	Airy + ME	Airy + PF + ME	Airy+ + ME, Airy + PF + ME
Control System (Servo)						
DLL, UD, SM	DLL	DLL, UD	DLL, UD, SM	UD	DLL	None
Structural Dynamics (Elastic)						
Turbine: FEMP + (Modal / MBS), Moorings: QSCE	Turbine: FEMP + (Modal / MBS), Moorings: UDFD	Turbine: MBS, Moorings: QSCE, UDFD	Turbine: MBS / FEM, Moorings: UDFD	Turbine: FEM, Moorings: FEM, UDFD	Turbine: MBS, Moorings: QSCE, MBS	Turbine: MBS, Moorings: QSCE, FEM

Airy+ – Airy wave theory +) with free surface corrections
BEM – blade-element / momentum
DLL – external dynamic link library
DNV – Det Norsk Veritas
DS – dynamic stall
GDW – generalized dynamic wake
FEMP – finite-element method P) for mode preprocessing only
MBS – multibody-dynamics formulation
ME – Morison's equation
MSC – MSC Software Corporation
PF – linear potential flow with radiation & diffraction
QSCE – quasi-static catenary equations
SM – interface to Simulink® with MATLAB®
UD – implementation through user-defined subroutine available
UDFD – implementation through user-defined force-displacement relationships

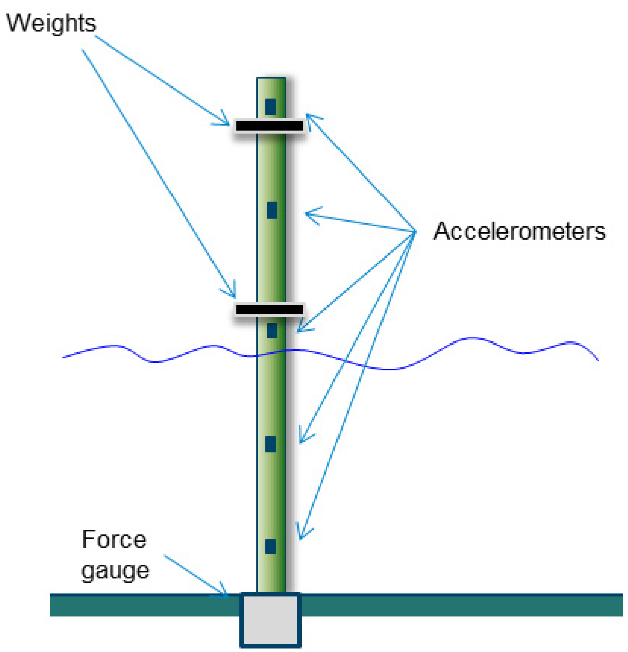
Data used for validation, NOWITECH,1

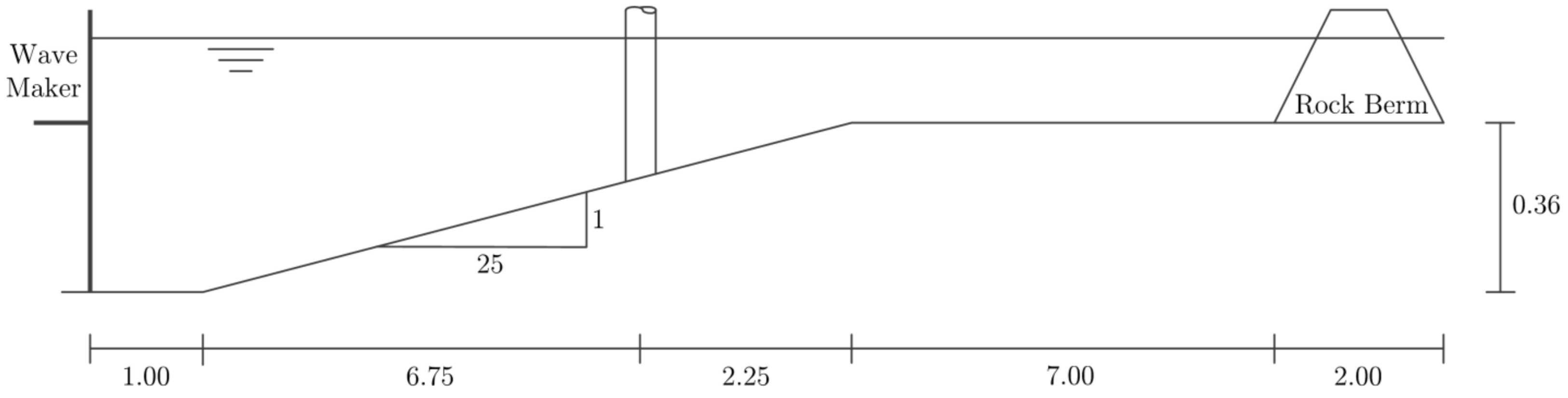
- HYWIND demo, full scale prototype measurements (partly available ?)
- Wave tank tests of fixed, rigid and flexible cylinders at MARINTEK and DTU (IEA OC5)
- Wave tank tests of semisubmersible at MARIN (IEA OC5)
- Full-scale data, bottom-fixed wind turbines from Alpha-Ventus (IEA OC5, ongoing)
- Wave tank test of Tension-Leg-Buoy at IFREMER, Brest (IFE/NMBU) MARINET
- Wave tank test (software-in-the loop) of OO Star Semi at ECN, Nantes (CENER/IFE/NMBU) MARINET
- Wave tank test of catenary mooring line with forced motion of fairlead, ECN, Nantes (CENER/IFE/NMBU)
- (Wave tank test of semi-submersible wind/wave energy converter (NTNU) MARINET ?)
- Wave tank test (software-in-the loop) of semi-submersible at MARINTEK
- Wave-tank test of monopile at MARINTEK (ongoing)

Data used for validation, NOWITECH,2

- Wind tunnel tests of wind turbine rotors at NTNU
- MEXICO and MEXNEXT wind tunnel tests, IEA projects

Fixed, flexible cylinders DHI and DTU. IEA OC5





Robertson, A., Wendt, F., Jonkman, J., Popko, W., Borg, M., Bredmose, H., Schlutter, F., Qvist, J., Bergua, R., Harries,R., Yde, A., Nygaard, T.A., De Vaal, J.B., Oggiano, L., Bozonnet, P., Bouy, L., Sanches, C.B, Garcia, R.G, Bachynski, E., Tu, Y., Bayati, I., Borisade, F., Shin, H., van der Zee, T., Guerinel, M. (2016). *OC5 Project Phase Ib: Validation of Hydrodynamic Loading on a Fixed, Flexible Cylinder for Offshore Wind Applications*. Energy Procedia 2016 ;Volume 94. pg. 82-101

Fixed, flexible cylinders, some results

Participant	Code	Wave Model (Reg/Irr)	Wave Elevation	Hydro Model	Structural Model	Number DOFs
4Subsea	OrcaFlex	FNPF kinematics	FNPF kinematics	ME	FE, RDS	160 elements 960 DOFs
GE	Samcef Wind Turbines	5th-Order Stokes/ Linear Airy	Stretching	ME	FE (TS), RD	13 elements 84 DOFs
DNV GL-ME	Bladed 4.6	6th- and 8th-Order SF/ Linear Airy	Measured	ME	FE (TS), MD	8 (CB)
DNV GL-PF	Bladed 4.6	Linear Airy	Measured	1st Order PF	Rigid	N/A
DTU-HAWC2	HAWC2	6th-and 8th-Order SF/Linear Airy and FNPF kinematics	Stretching and FNPF kinematics	ME	FE (TS), RDS	20 elements, 126 DOFs
DTU-HAWC2-PF	HAWC2	6th-and 8th-Order SF/Linear Airy	Stretching	McCamy & Fuchs	FE (TS), RDS	31 elements, 192 DOF
DTU-BEAM	OceanWave3D	FNPF kinematics	FNPF kinematics	ME+Rainey	FE (EB), RD	160 DOFs
IFE	3Dfloat	FNPF kinematics	FNPF kinematics	ME	FE (EB), RDS	62 elements, 378 DOFs
IFE-CFD	STAR CCM	CFD	CFD-derived	CFD	Rigid	N/A
IFP-PRI	DeeplinesWind	3rd-Order SF/ Linear Airy	Measured	ME	FE	200 elements
UC-IHC	IH2VOF	FNPF kinematics	FNPF kinematics	ME	Rigid	N/A
MARINTEK	RIFLEX	2nd-Order Stokes and FNPF kinematics	Measured and FNPF kin.	ME	FE(E-B), RDS, FS	167 elements, 1002 DOFs
NREL-ME	FAST	2nd-Order Stokes and FNPF kinematics	Measured and FNPF kin.	ME	FE (TS), MD	4 (CB)
NREL-PF	FAST	2nd-Order Stokes	Measured	2nd-Order PF	Rigid	N/A
NTNU-Lin	FEDEM 7.1	Linear Airy	None	ME	FE (EB), RD	13 elements, 84 DOFs
NTNU-Stokes5	FEDEM 7.1	5th-Order Stokes	None	ME	FE (EB), RD	13 elements, 84 DOFs
NTNU-Stream	FEDEM 7.1	Stream Function	None	ME	FE (EB), RD	13 elements, 84 DOFs
PoliMi	POLI-HydroWind	2nd-Order Stokes	None	ME	FE (EB), RD	23 elements, 69 DOFs
SWE	SIMPACK +HydroDyn	2nd-Order Stokes	None	ME	FE (TS), MD	50
UOU	UOU + FAST	2nd-Order Stokes	None	ME	Rigid	N/A
WavEC	Wavec2Wire	2nd-Order Stokes	Measured	2nd-/1st-Order PF	Rigid	N/A
WMC	FOCUS6 (PHATAS)	FNPF kinematics	FNPF kinematics	ME	FE (TS), MD	12 (CB)

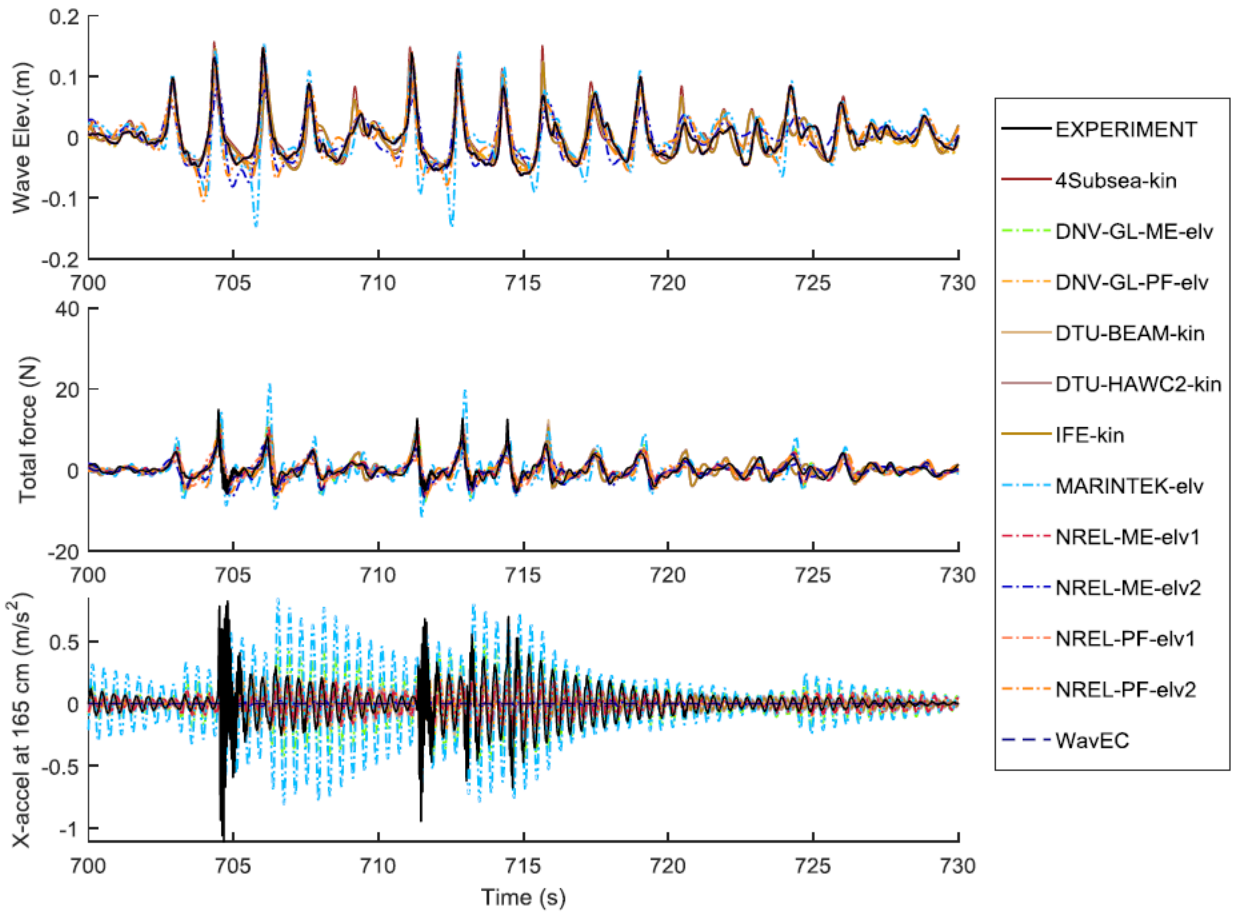
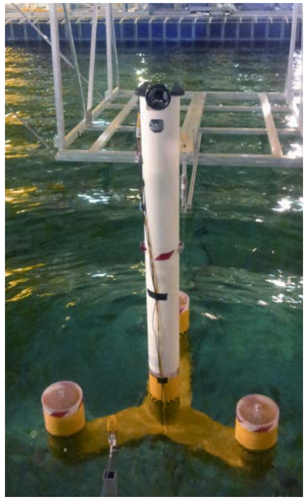


Figure 12. Validation of simulated wave elevation, force, and acceleration response against measurement for Test 7 (shallow water, irreg. waves)

OO Star Semi, ECN, Nantes



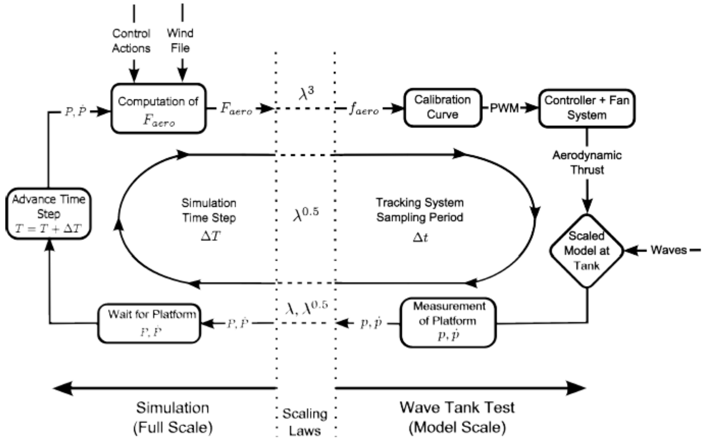
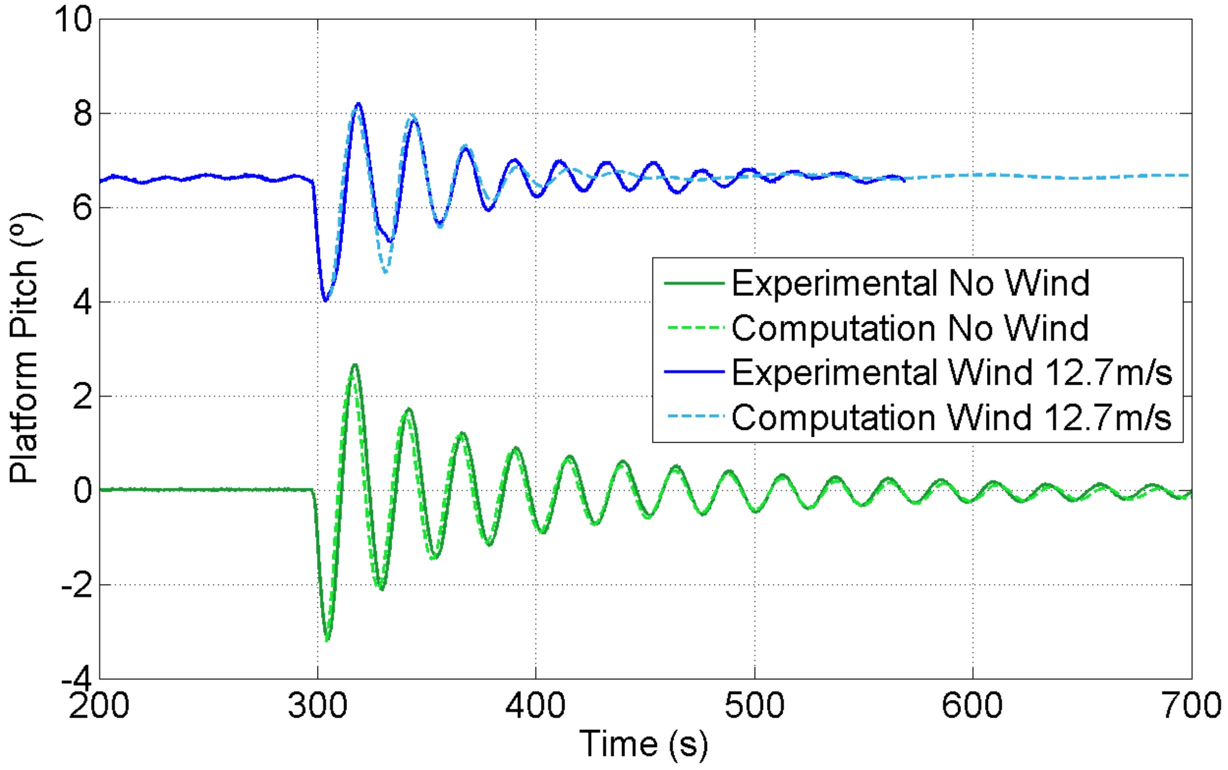


Figure 2. Software-in-the-Loop Method Diagram

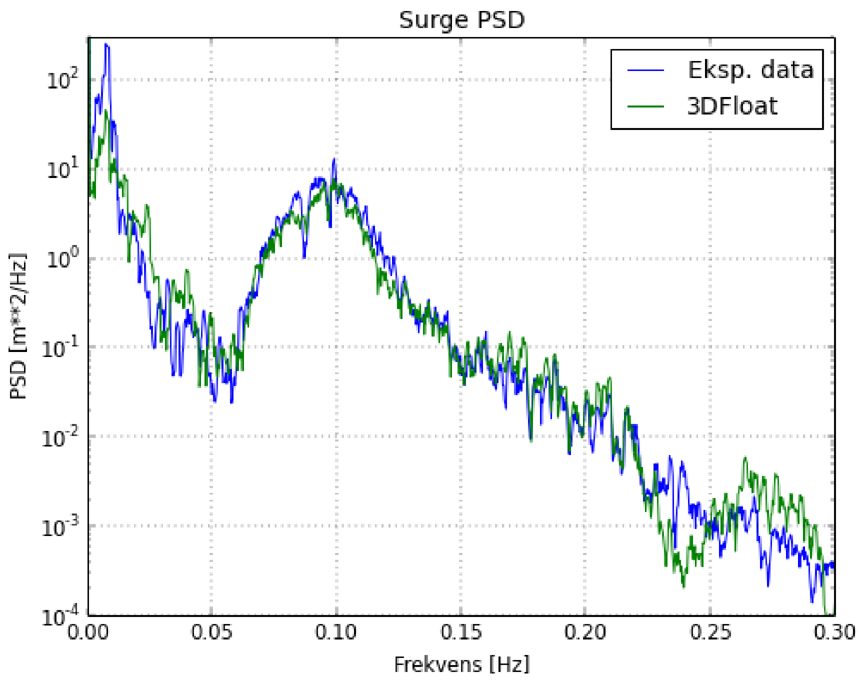
Azcona, J., Bouchotrouch, F., González, M., Garciand, J., Munduate, X., Kelberlau, F. and Nygaard, T.A. (2014). *Aerodynamic Thrust Modelling in Wave Tank Tests of Offshore Floating Wind Turbines Using a Ducted Fan*. Journal of Physics: Conference Series 524 (2014) 012089.

Azcona, J., Munduate, X., González, L., and Nygaard, T.A. (2017). *Experimental Validation of a Dynamic Mooring Lines Code with Tension and Motion Measurements of a Submerged Chain.* Ocean Engineering 2017, Vol. 129 , pg. 415-427.

OO Star Semi, some results

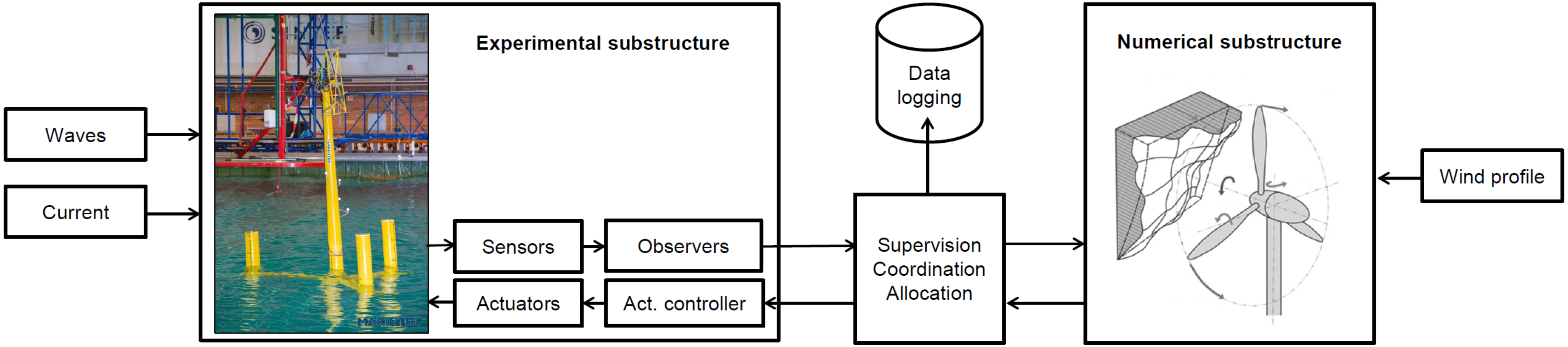


From Azcona et al., 2014



From Masters’s thesis of Engelsvold, NMBU, 2015

Semisubmersible, MARINTEK



[1] Thomas Sauder, Valentin Chabaud, Maxime Thys, Erin E. Bachynski, Lars Ove Sæther (2016). “Real-time hybrid model testing of a braceless semisubmersible
wind turbine: Part I: The hybrid approach”. In 35th International Conference on Ocean, Offshore and Arctic Engineering, no. OMAE2016-54435.

• [2] Erin E. Bachynski, Valentin Chabaud, Thomas Sauder (2015) "Real-time hybrid model testing of floating wind turbines: sensitivity to limited actuation".
Energy Procedia. vol. 80.

Semisubmersible, MARINTEK, some results

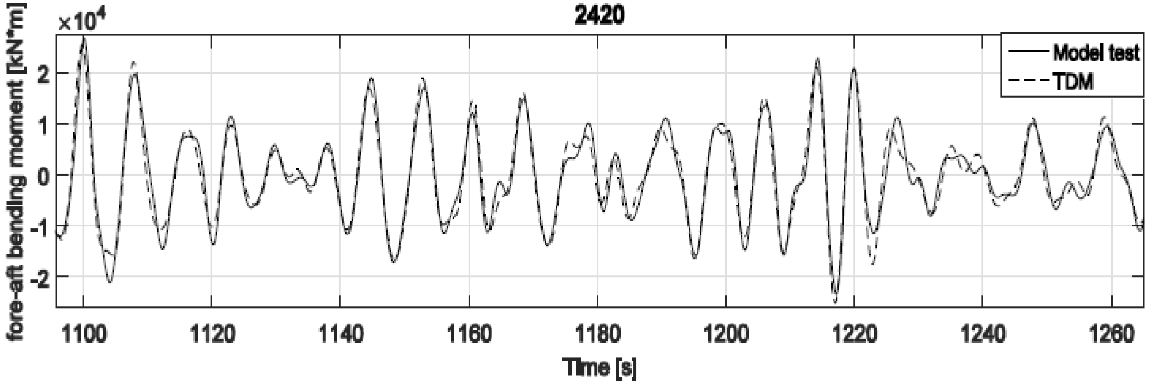
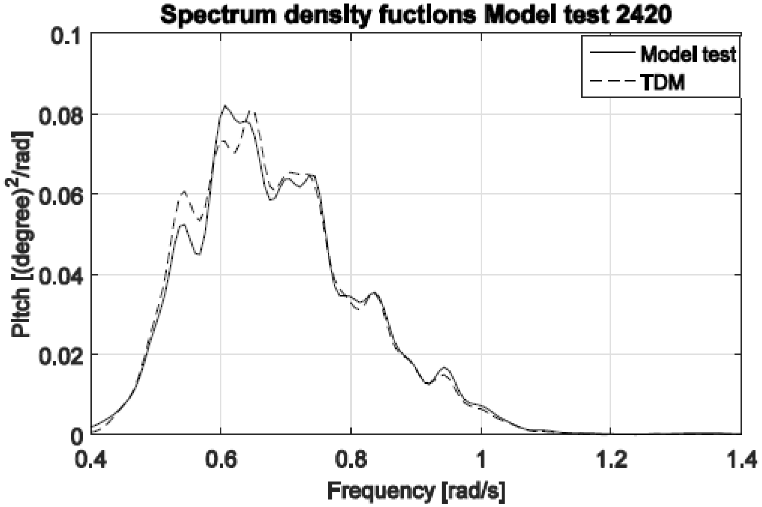


Figure 12 Part of measured and simulated fore-aft bending moment, moderate wave only, $H_s = 3.6$ m and $T_p = 10.2$ s



Luan, C. et al. (2017). Experimental validation of a time-domain approach for determining sectional loads in a floating wind turbine hull subjected to moderate waves. Deepwind 2017.

Semisubmersible, MARIN. IEA OC5

Participant	Code	Aerodyn.		Hydrodynamics							Moorings		
		Dyn. Wake	Unst. Airfoil	2^{nd} + WK	1^{st} PF	2^{nd} PF	ME	Meas. Wave	Stretch	Inst. Pos.	Dyn.	Hydro Exc.	Seabed Fric.
4Subsea	OrcaFlex-FAST v8												
CENER	FAST v6 + OPASS												
CENTEC	FAST v8												
DNV GL	Bladed 4.8												
DTU ME	HAWC2												
DTU PF	HAWC2												
ECN-MARIN	aNySIM-PHATAS v10					Diff.-only							
IFE	3DFloat												
IFP_PRI	DeepLines Wind V5R2												
NREL PF	FAST v8												
NREL ME	FAST v8												
POLIMI	FAST v8.15			Diff.-only									
Siemens PLM	Samcef Wind Turbines												
Tecnalia F7O	FAST v7 + OrcaFlex 9.7												
Tecnalia F8	FAST v8.16												
UC-IHC	Sesam												
UOU	UOU + FAST v8												
UPC	UPC + FAST												
UTokyo	NK-UTWind												
WavEC FAST	FAST v8												
WavEC FF2W	FF2W												

Robertson, A. et al. (2017) OC5 Project Phase II: Validation of Global Loads of the DeepCwind Floating Semisubmersible Wind Turbine. Deepwind 2017

Semisubmersible, MARIN, IEA OC5

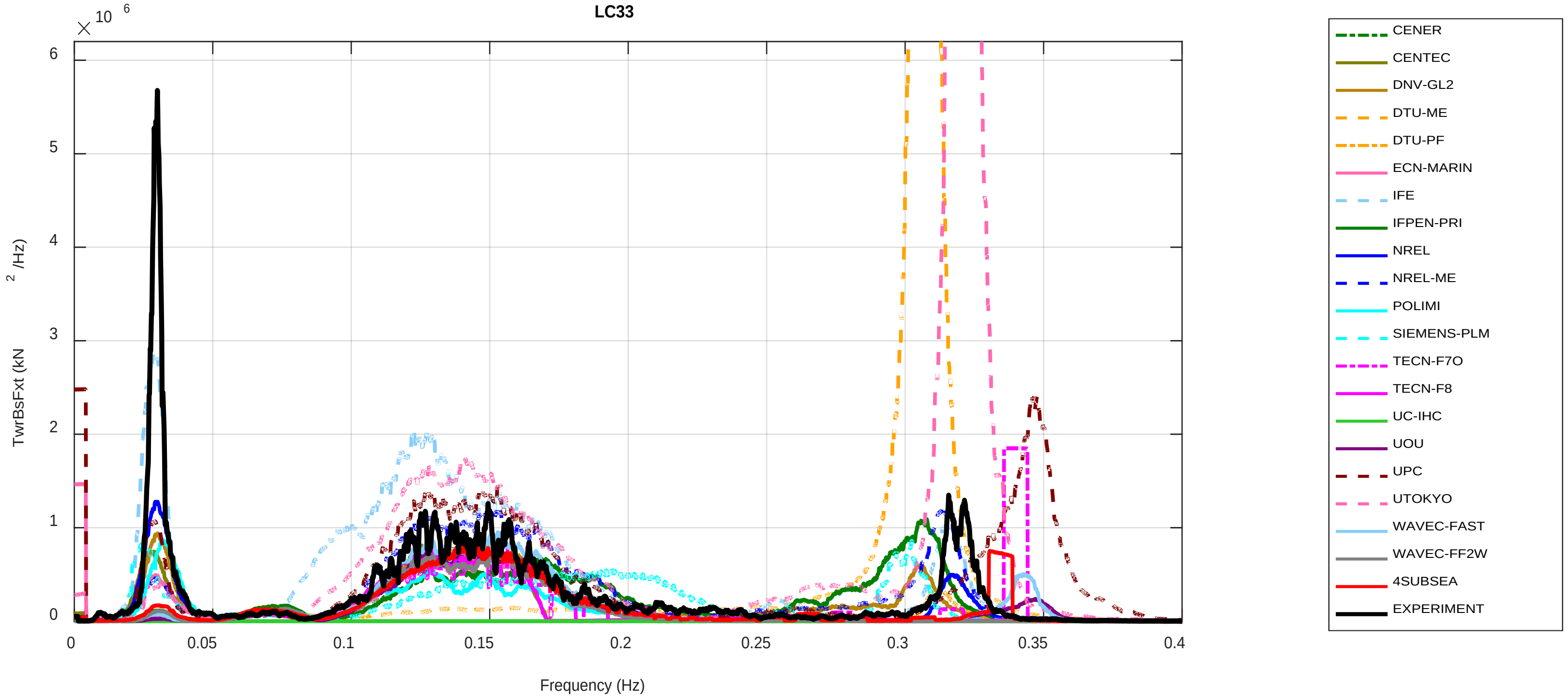


Fig. 9. PSD of the tower-base shear force for operational wave excitation, using a significant wave height of 7.1 m and peak period of 12.1 s

Evolution during NOWITECH

- Higher-order wave kinematics
- More detailed load models
- Experience with what approaches can be used for different types of floaters
- Advanced rotor aero-elasticity
- Soil/structure interaction
- From verification (code to code) to validation (experimental data)
- Education and training of analysts. The complexity of offshore wind turbines makes the person doing the analysis as important as which model is being used.

Will it pay off ?

Potential and realized economic impacts of NOWITECH innovations

Impello Management AS

Frode Iglebæk

24.05.2017

SIMA (SIMO/RIFLEX) and 3Dfloat – NPV estimate

CASHFLOW AND NPV [MEUR]	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	…	NPV MEUR
Investments - 3 years prior to operation	2,8	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	-	-	-		
Annual saving - floater parks (nominal values)	-	-	-	63.1	98.6	98.6	98.6	98.6	98.6	98.6	98.6	98.6	98.6	98.6		
Annual saving - monopile parks (nom. values)	-	-	-	133.4	208.6	208.6	208.6	208.6	208.6	208.6	208.6	208.6	208.6	208.6		
Net profit/yr (nominal values)	-2.8	-4.3	-4.3	192.2	303.0	303.0	303.0	303.0	303.0	303.0	303.0	307.3	307.3	307.3		2 183
Net profit (real values)	**-2.8**	**-4.4**	**-4.5**	**204.0**	**327.9**	**334.5**	**341.2**	**348.0**	**355.0**	**362.1**	**369.3**	**382.1**	**389.7**	**397.5**		**2 551**

	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Total new installations (GW) – **Central scen.**				2.8	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3
Applicable new installations (GW) **(100 %)**				2.8	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3
Accumulated new applicable installations				**2.8**	**7.1**	**11.4**	**15.7**	**20.0**	**24.3**	**28.6**	**32.9**	**37.2**	**41.5**	**45.8**

Key assumptions

- The simulation tools are applicable for all new European wind farms set in operation in the 2020-2030 period.
- This is applicable for both floating and bottom fixed turbines.
- Annual savings are derived from reduced materials use for tower, substructure, mooring and more). This is applicable for both floaters and monopile structures.
- Additional required investments is 1 MEUR/GW park.
- Reduced risk (CAPEX) is not included in the calculations.

ASSUMPTIONS		
Wind farm size	1,0	GW
Project duration (technology obsolete after this)	10	yrs
Market relevance (applicable new installations)	100	%
Materials weight - floater	3 670	tons
Materials weight - monopile	1 370	tons
Reduced materials use (tower, substructure, mooring)	5	%
Unit costs (materials)	5,0	EUR/kg
Materials savings per turbine - floater	918	kEUR
Materials savings per turbine - monopile	343	kEUR
Turbine size	6.0	MW
No. of turbines per wind park (1 GW)	167	turbines
Materials savings per 1 GW - floater park	153	MEUR
Materials savings per 1 GW - monopile park	57	MEUR
Floater park share	15	%
Monopile park share	85	%
Total additional investments per 1 GW park	1.0	MEUR
Discount rate (cost of capital)	5	%

Quantified potential: NPV ≈ 2500 MEUR

Unexpected, positive side effects

- New conceptual designs for long, floating bridges for E39 required time-domain simulations with full coupling between a flexible structure, turbulent wind and irregular waves.
- The ability of 3DFloat and SIMO/Riflex to offer this capability is a direct result of floating wind turbine work in NOWITECH.
- More accurate time-domain simulations can potentially reduce overly concervative designs, and thereby costs. 1% of cost reduction for a bridge with cost 20e9 NOK (20 billion, milliarder) is 200 MNOK. The work package for integrated models in NOWITECH had a total cost of ?? MNOK of the total research budget of 320 MNOK.

Conclusions and the way forward

- The integrated models have improved considerably over the last ten years
- Education and experience gained for engineers is important as well
- We still have a lot to do; give 10 groups identical models and identical geomtery definitions, and you will still see some spread of the results !
- Computational Fluid Dynamics (CFD), not treated in this presentation will play an increasing role, both for hydrodynamics and aerodynamics, in full coupling with structural dynamics.