FRANCE
ENERGIES
MARINES

An engineering method to assess extreme breaking wave loads in the design of FOWTs

J.-F. Filipot, P. Renaud, M. Prevosto (FEM), F. Hulin (FEM/Ifremer/ENSTA Br.), M. Battle (FEM/ENPC), A. Tassin (Ifremer), J. Harris (ENPC), N. Jacques (ENSTA Br.), C. Peyrard, M. Teles (EDF), A. Nestegard, E. Asp (DNV)

January 16, 2024

The DIMPACT project (2020-2023)

Objectives: slamming loads on FOWT

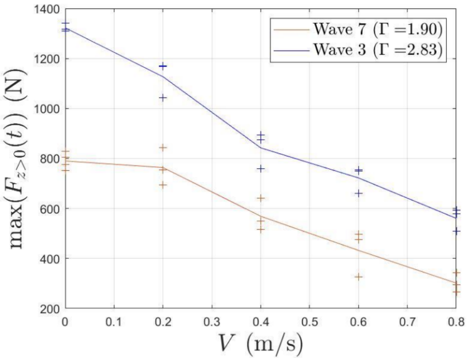
- Investigate effects of FOWT motions/tilt on slamming loads
- Derive appropriate slamming engineering formula
- Implement it in FOWT-coupled models

FOWT surge motion and tilts effect on slamming loads

Ifremer's wave flume : 2m deep, 50m long

- Segment mockup with 4 cell forces, mounted on a hexapod
- 1/25 spar-type floater (Hywind Demo)
- tilt and surge motions ranges obtained from FOWT-coupled modeling in high seas (4 different floaters)
- force measurements corrected for structure vibration signature

→ Surge motions should be accounting for!



Maximum peak force on the cylinder as a function of surge motion velocity (results from F. Hulin)

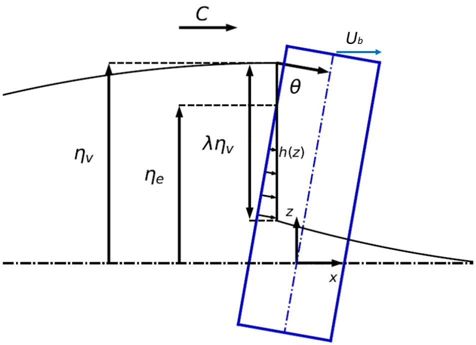
Slamming loads on a moving/tilted FOWT

Approach : *Renaud et al.* [2023b]

$$F_s = \rho R \int_{(1-\lambda)\eta_v}^{\eta_e(t)<\eta_v} C_s (U(z) - U_b)^2 \cos^2 \theta dz$$

- Account for tilt θ and surge motion U_b
- C_s varies as a function of penetration depth $h(z,t)$
- $U(z)$ used instead of C for fluid velocity

$\rightarrow$ will be referred to in DNV-RP-C205



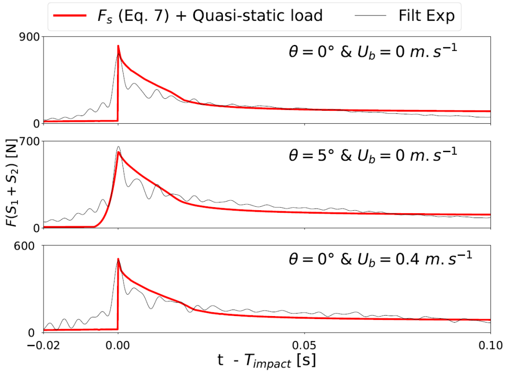
Slamming loads on a moving/tilted FOWT

Approach : *Renaud et al.* [2023b]

$$F_s = \rho R \int_{(1-\lambda)\eta_v}^{\eta_e(t)<\eta_v} C_s(U(z) - U_b)^2 \cos^2\theta dz$$

- Account for tilt θ and surge motion U_b
- C_s varies as a function of penetration depth $h(z,t)$
- $U(z)$ used instead of C for fluid velocity

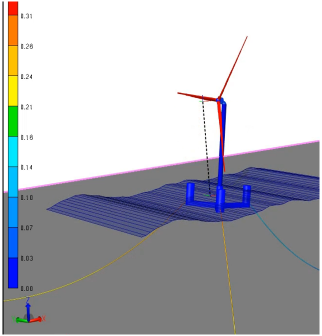
→ will be referred to in DNV-RP-C205



Inferring realistic slamming loads from linear sea states

The Windfloat pioneer FOWT, from Principle Power Inc, deployed in Portugal.

Inferring realistic slamming loads from linear sea states



A FOWT in linear high seas (courtesy of T. Coquio).

FRANCE
ENERGIES
MARINES

Inferring realistic slamming loads from linear sea states

Let's imagine that the numerical sea state is the linear realization of the real sea state.

If so :

1. Would we be able to detect the breaking wave in the linear sea state?
2. Would we be able to assess the magnitude of the slamming load from the properties of the linear ”breaking” wave?

Can we detect breaking onset in linear sea states?

Irregular waves - direct validation :

- Model : Fully Nonlinear Potential Flow model from *Grilli and Subramanya* [1996], validated with wave tank experiment [*Hulin et al.*, 2022]
- $kd \in [1.4 - 1.7]$
- wave conditions : 12 wave packets (1D), JONSWAP spectrum, varying breaking severity

$$u_{nl}/c_{nl} = 0.85^{*} \leftrightarrow u_{lin}/c_{lin} = 0.34$$

Barthelemy et al. [2018]

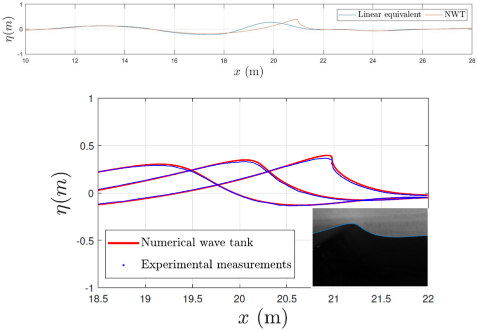
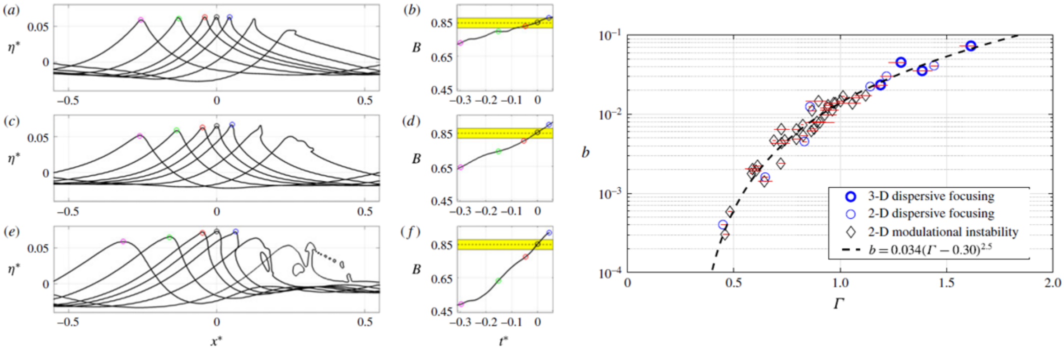


Figure: *Top : linear wave packet and its FNPF "twin", bottom : Comparison between FNPF model free surface and experiment. Results from F. Hulin.*

FRANCE ENERGIES MARINES

Assessing breaking wave severity, results from *Derakhti et al.* [2018]



Left : different breaking waves and the evolution of $B = u/c$ as a function of time, right : relation between breaking dissipation strength and breaking severity $\Gamma = T_b \frac{du/c}{dt}|_{u/c=0.85}$
Extracted from *Derakhti et al.* [2018].

FRANCE ENERGIES MARINES

Assessing slamming loads from linear wave properties

DIMPACT Slamming force [*Renaud et al.*, 2023a]

$$F_s(t) = \rho R \int_{(1-\lambda)\eta_v}^{\eta_e(t)<\eta_v} C_s(U(z) - U_b)^2 \cos^2\theta dz$$

How to assess $F_s(t)$ from linear waves?

- $\lambda = 0.5\tanh(0.8\Gamma)$ [*Batlle Martin et al.*, 2023]
- $\Gamma = 4.\Gamma_{lin}$ [*Prevosto et al.*, 2024]
- C and η_v from nonlinear regular wave theory [*Clamond and Dutykh*, 2018]
- $U(z) = C\left(\frac{z}{\eta_b}\right)^{\alpha}, \alpha = 0.48 + 4.72e^{0.5\Gamma}$

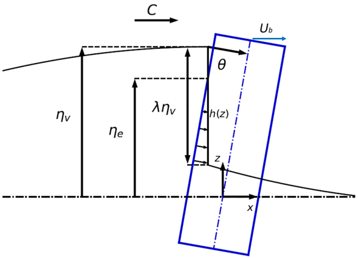


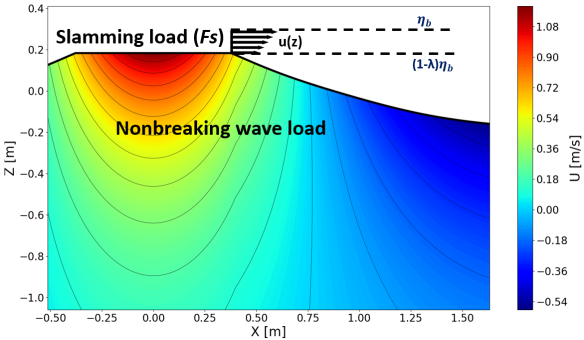
Figure: *Sketch of the impact of a breaking wave on a inclined and moving cylinder and governing parameters from Renaud et al. [2023a]*

Practical implementation in FOWT coupled models

Approach

- "breaking wave" detected in linear sea states
- Nonlinear wave parameters (λ, $U(z)$, η_v) assessed from linear wave
- breaking load F_s from *Renaud et al.* [2023a]
- non-breaking loads : (truncated) regular nonlinear wave with linear-eq. energy + non-breaking load model [*Renaud et al.*, 2023b]

$$F_s(t) = \rho R \int_{(1-\lambda)\eta_v}^{\eta_e(t)<\eta_v} C_s (U(z) - U_b)^2 \cos^2 \theta dz$$



Validation with wave flume experiments

Wave flume experiment

- Ifremer's wave flume (40.5 x 2m)
- $kd \in [1.4 - 1.7]$
- Segmented mockup (load cells)
- Mounted on an hexapod
- Varying steepness, breaking location, wave-cylinder motion, cylinder tilt

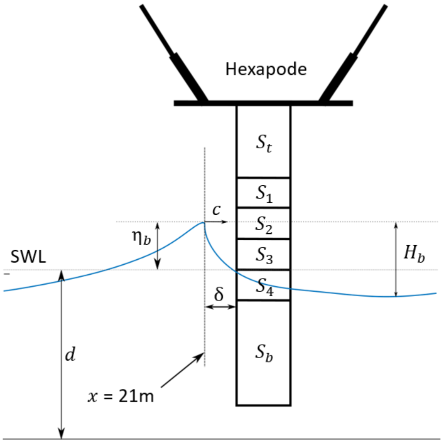
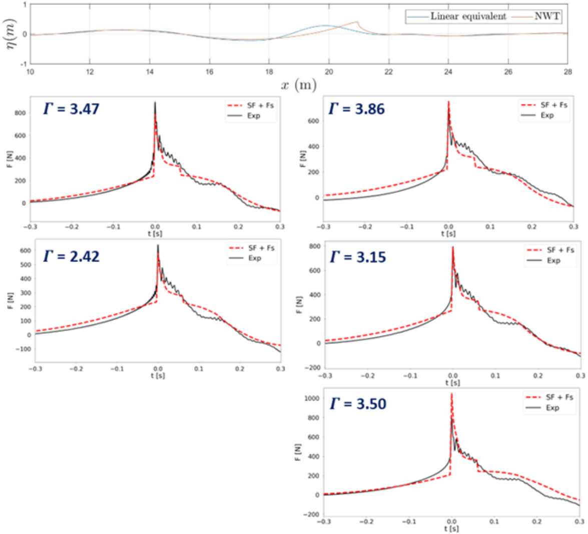


Figure: *Courtesy of F. Hulin (FEM/Ifremer/ENSTA-Br.) and A. Tassin (Ifremer).*

Validation with wave flume experiments



FRANCE ENERGIES MARINES

Conclusions & perspectives:

A method to assess slamming loads in FOWT coupled model

Main Features

- detection of breaking waves in linear sea states
- assessement of wave breaking severity/loads from linear waves

limitations :

- Validation over 1D, few waves (packets), narrow kd range

Transfer to the industry :

- Slamming method implement in DIEGO (EDF) and in Open_FAST (NREL)
- Slamming formula by *Renaud et al.* [2023a] to be referred to in DNV RCP_C205

FRANCE
ENERGIES
MARINES

Overview of DIMPACT results

New wave loads models
→ Renaud & al. (OE2023)

Linear wave breaking onset definition
→ Hulin & al. (2024a)

Vibration corrections in hydrodynamic loads
→ Tassin & Hulin (JSV2023)

CFD model for slamming loads
→ Batlle & al. (ISOPE2022)
→ Batlle & al. (CE2023)

Design sea states with breaking waves
→ Prevosto & al. (OE2024)

Relation between breaking severity and load
→ Hulin & al. (2024b)

Wave loads on a moving/tilted FOWT
→ Renaud & al. (OMAE2023)
→ Hulin et al. (JH2022)

Slamming loads from linear waves
→ Renaud & al. (OE2024)

Full methodology & FOWT coupled model
→ Filipot & al. (OE2024)

Next Project : DIMPACT+, floating and bottom-fixed OWT

Objectives :

- Validate/extend the approach with more realistic sea states, wider range of kd, bottom slope
- Benchmark with DeRisk project tools
- Accumulate knowledge from field measurements
- transfer in OWT coupled models and improve standards

Timeline :

- submission end of june (FEM's call for proposals)
- launch : October 2024 (3-years)

if interested: jean.francois.filipot@ite-fem.org

Thank you!

References I

Barthelemy, X., M. Banner, W. Peirson, F. Fedele, M. Allis, and F. Dias, On a unified breaking onset threshold for gravity waves in deep and intermediate depth water, *Journal of Fluid Mechanics*, *841*, 463–488, 2018.

Batlle Martin, M., J. C. Harris, J.-F. Filipot, F. Hulin, A. Tassin, and P. Renaud, Deep water focused breaking wave loads on a fixed cylinder, *Coastal Engineering*, *(in press)*, 104,397, doi:10.1016/j.coastaleng.2023.104397, 2023.

Clamond, D., and D. Dutykh, Accurate fast computation of steady two-dimensional surface gravity waves in arbitrary depth, *Journal of Fluid Mechanics*, *844*, 491–518, 2018.

Derakhti, M., M. L. Banner, and J. T. Kirby, Predicting the breaking strength of gravity water waves in deep and intermediate depth, *Journal of Fluid Mechanics*, *848*, 2018.

Grilli, S. T., and R. Subramanya, Numerical modeling of wave breaking induced by fixed or moving boundaries, *Computational Mechanics*, *17*(6), 374–391, 1996.

FRANCE ENERGIES MARINES

References II

Hulin, F., M. Batlle Martin, P. Renaud, A. Tassin, J.-F. Filipot, and N. Jacques, Experimental investigation of the hydrodynamic loads induced by breaking wave impacts on a spar-type floating offshore wind turbine substructure , in *Proc. Journées de l'Hydrodynamique*, p. 14 pp., 2022.

Prevosto, M., J.-F. Filipot, F. Hulin, P. Renaud, A. Tassin, and N. Jacques, Deep water focused breaking wave loads on a fixed cylinder, *Coastal Engineering*, to be submitted, 2024.

Renaud, P., M. Batlle Martin, Y.-M. Scolan, J.-F. Filipot, J. C. Harris, and F. Hulin, Semi-analytical load models describing the progressive immersion of a fixed vertical cylinder in a breaking wave, *Ocean Engineering*, *276*, 114,116, 2023a.

Renaud, P., F. Hulin, M. Batlle Martin, Y.-M. Scolan, A. Tassin, N. Jacques, J. C. Harris, and J.-F. Filipot, Semi-analytical load models accounting for the tilt and motion of a cylinder impacted by a plunging breaking wave, in *Proc. 42th International Conference on Ocean, Offshore and Arctic Engineering*, p. 10 pp., 2023b.