Analysis of a Wave Energy Converter with a Particular Focus on the Effects of Power Take-Off Forces on the Structural Responses

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Outline

Failures of WEC’s

Non-linear WEC model

Control mechanism
  Unconstrained control: Passive and Active
  Constrained control

Structural model

Conclusion
Failure I: Motions, Power extraction

- A good wave energy converter is a good wave absorber!

**Figure:** Detail of the connection joint between arm and float
Failure II: Wear and fatigue damage

- The devil lies in the detail!

**Figure:** Detail of the connection joint between arm and float
Failure III:
Inadequate design, absence of safety system

- Safety system to reduce wave loads in extreme events

**Figure:** Mooring line failure in a five years extreme event, January 2012
PhD Outline

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PhD Outline

Wave Spectrum
Jonswap, Pierson-Moskovitz.

Directionality functions to account for different incident wave angles

Linear Hydrodynamic Potential Flow Analysis
AQWA-LINE / WAMIT

CeSOS PhD guest stay

Spectral-based fatigue Analysis

Detailed FE-analysis

Stress Concentration Factors (SCF)

Global FE-analysis

Quasi-Static response Analysis

Complex load cases

Paper 1
Hybrid frequency-time domain model

Paper 2
Spectral-based fatigue analysis

Paper 3
Validation of the linear numerical model by experiments

Paper 4
Power matrices for different control strategies

Paper 5
Validation of the non-linear numerical model by experiments

Paper 6
Structural modeling, Quasi-static approach

Paper 7
Fatigue analysis, control

Fatigue Analysis based on Rain-flow counting cyclic analysis

Extended Abstract 1
Transient structural analysis

Extended Abstract 2
Direct integration vs. state-space modeling

Frequency response analysis (RAO)

Site specific scatter diagram

Active Control

Passive Control

Power Matrix and Annual Energy Production, AEP

Effect of nonlinear motions on structural response

Extended Abstract 1

Extended Abstract 2

Non-linear hydrostatic moment, drag forces

Quasi-Static response Analysis

Stress Concentration Factors (SCF)

Global FE-analysis

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Linear Hydrodynamic Potential Flow Analysis
AQWA-LINE / WAMIT

3rd SDWED Symposium
Aalborg University, Denmark
Case study: Wavestar arm

- Structural response analysis: stress analysis in the arm.
- The stress amplitudes vary in function of the applied control mechanisms.

Figure: Wavestar arm with float, a) Protection mode b) Operational mode.
Laboratory Model 1:20
Representing the Wavestar Prototype WEC
Wave Excitation Force/Moments
Power Take Off Mechanism

- Lever arm $d_a$ from the cylinder force $F_c$ to the moment $M_c$ is depending on the angular rotation $\theta(t)$ of the arm.
- A time domain analysis is needed to account for this effect.

\[ F_c(t) = k_c \Delta l(t) + c_c \Delta \dot{l}(t) = k_c d_a(t) \theta(t) + c_c d_a(t) \dot{\theta}(t) \]
\[ M_c(t) = d_a(t)^2 \cdot (c_c \dot{\theta}(t) + k_c \theta(t)) \]
\[ \mathcal{P}_c = \langle \dot{\theta}(t) d_a(t) F_c(t) \rangle \]
\[ F_{cx} = F_c \sin(\gamma(\theta(t))) \]
\[ F_{cy} = F_c \cos(\gamma(\theta(t))) \]
Variable lever arm $d_a(t)$

- Lever arm in function of the pitch angle $\theta(t)$.
- Effect on the power production and the maximum control force.

Sinusoidal wave $H = 1.0\, m$, $T_s = 10\, s$

**Figure:** Lever arm $d_a$ as a function of the $\theta$, left: $-$: $d_1/d_2 = 0.5$, $-.-$: $d_1/d_2 = 0.6$, $--$: $d_1/d_2 = 1.0$, $---$: static referential state.
Time domain model

- Below: equation of motion (EQM) in the time domain, $\theta(t)$: Pitch.
- EQM is solved with a Newmark numerical integration scheme.
- The hydrostatic coefficient $K$ is treated non-linear.

\[
\begin{align*}
M \ddot{\theta}(t) + \int_{-\infty}^{\infty} k(t - \tau) \dot{\theta}(\tau) + K(\theta(t)) &= M_{ex}(t) - M_{c}(t) \quad (1) \\
M_{c}(t) &= d_a(t)^2 \cdot (c_c \dot{\theta}(t) + k_c \theta(t)) \quad (2)
\end{align*}
\]
Non linear hydrostatic stiffness coefficient

- Undisturbed wave elevation is used for buoy position tracking

**Figure:** Hydrostatic force vs. pitching angle.
Non-linear numerical modeling and experimental testing of a point absorber wave energy converter

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ABSTRACT

A time domain model is applied to a three-dimensional point absorber wave energy converter. The dynamical properties of a semi-submerged hemisphere oscillating around a pivot point where the vertical height of this point is above the mean water level are investigated. The numerical model includes the calculation of the non-linear hydrostatic restoring moment by a cubic polynomial function fit to laboratory test results. Moreover, moments due to viscous drag are evaluated on the oscillating hemisphere considering the horizontal and vertical drag force components. The influence on the motions of this non-linear effect is investigated by a simplified formulation proportional to the quadratic velocity. Results from experiments are shown in order to validate the numerical calculations. All the experimental results are in good agreement with the linear potential theory as long as the...
Method

- Newmark scheme: $\Delta t = 0.01 \text{ s}, \gamma = 1/2, \beta = 1/6$, (Linear acceleration method)
Power wave spectrum

- Jonswap type, parametrized
- Random phase method

\[ S_\eta(f) = \frac{1.4}{\gamma} \frac{5}{16} H_s^2 f_p^4 f^{-5} \gamma \alpha \exp\left(-\frac{5}{4}\left(\frac{f_p}{f}\right)^4\right) \]

\[ S(f)[m^2s] \]

\[ g=1 \quad g=3 \quad g=5 \quad g=7 \]

- \( \gamma = \) peak shape parameter
- \( H_s = 4\sqrt{m_0} \)
- \( f_p, T_p = 1.406 \cdot T_z, T_z = \sqrt{\frac{m_0}{m_2}}, \gamma = 1.0 \)
- \( \delta = \sqrt{1 - \frac{m_1^2}{m_0 m_2}} \)
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Unconstrained control

- No limits on the control force $F_c$
- Arbitrary large angular displacements $\theta(t)$
- Irregular wave, $H_s=2.4m$, $T_p=7.5s$, simulation time $t=10'800s$ (3h).

Passive Control, $k_c/k_{hyst} = 0$

Active Control, $k_c/k_{hyst} = -0.13$
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- Force constrained: Limits due to the saturation in the hydraulic actuator system:

\[ F_{c, \text{min}}(t) \leq F_c(t) \leq F_{c, \text{max}}(t) \] (4)

- Amplitude constrained: Absorber is not allowed to jump out of the water.

\[ \theta(t)_{\text{min}} \leq \theta(t) \leq \theta_{\text{max}} \] (5)

- Stress responses including force and amplitude constraints have to be calculated in the time-domain.
Structural Model
Analysis of the Connection Joints

Connection 1 "W3" SN-curve

Connection 2 "F" SN-curve

Connection 3 "F" SN-curve

Connection 4 "F" SN-curve
Stress response functions

\[ H_\sigma(\omega|\theta) \text{ [MPa/m]} \]

\[ T_z \text{ [s]} \]

\[ H_\sigma(\omega|\theta) \text{ [MPa/m]} \]

\[ T_z \text{ [s]} \]
Accumulated Fatigue Damage in a Joint

- Accumulated fatigue damage in Connection Joint 3
Accumulated fatigue damage in Connection Joint 4
Conclusion

- Reactive control has a significant impact on the stress amplitudes on the Wavestar arm.

- By introducing reactive control \((k_c/k_{hyst} = -0.13)\) the average power is increased by a factor of 2 whereas the nominal stresses are increased by a factor of 4.
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