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STRUCTURAL DESIGN OF WAVE ENERGY DEVICES

Overview of Wave to Wire Models

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by

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Table of Contents

Introduction

A “Wave to Wire” (W2W) model is a numerical tool that can calculate the power output from a specified Wave Energy Converter (WEC), under specified ocean wave conditions. The tool can be used to assess and optimize the performance of a Wave Energy Converter (WEC) design and provide knowledge of the WEC behavior – such as motions and forces – in its operating wave conditions.

Typically, the simulation concerns a full-scale WEC design validated against small-scale experimental studies in wave tanks. “Wave to Wire Modelling” can be carried out using commercial software packages, but recently free alternatives have also become available.

A W2W model can typically offer the following options:

- Time series of the power output
- Details concerning the efficiency of the Power Take Off (PTO) system
- Implementation of different (optimal) control strategies
- Time series of structure motions and mooring line forces
- Fatigue loads on structural components which are exposed to high cyclic loading
- Dynamical prediction of the response of a wave energy converter in moderate sea states.

The W2W modeling is traditionally concerned with the operating wave conditions in which the WEC produces power, but can also be extended to include non-linear and viscous effects for assessing motions and loads in extreme and survival conditions.

The design and survival issues related to the WEC design are also part of the SDWED project, with the focus on structural integrity, motions, end stop loads, mooring forces and investigating possible failure modes.

Objectives

The purpose of this report is to provide an overview of some of the many aspects that feed into W2W models and also to give a summary of some of the tools available.

Summary and conclusions

The development of W2W models in combination with physical model experiments helps validate both the experiments and the numerical model. There are many wave energy converters under development of different geometry, using different operating principles, PTO's and mooring systems – and thus a W2W tool has to be very flexible, or composed of blocks with focus on system parts such as Power Take Off design, mooring design, structural design, or array interaction effects.

Software tools to assist in modelling WECs are commercially available, but such software is rather expensive and cannot be modified by the user for specific needs. Case studies in the SDWED project on different WEC systems, have demonstrated how "low-cost" numerical modelling and testing can be completed depending on device configuration and purpose.

Other new initiatives promise open-source codes to become available sometime in the future. For example, the U.S. Department of Energy has initiated the so-called "Water Power Program", the purpose of which is to develop open-source software to simulate the generated electric power of different wave energy converter designs. This could lead to a simple common tool that would allow the developer to focus on the geometrical and structural definition of the Wave Energy Converter and the software would provide results concerning the performance.

This report will provide descriptions of the elements feeding into a W2W model, as illustrated below:

1. WEC design data
2. Hydrodynamic pre-processor
3. Wave and Current Parameters
4. PTO & Control
5. WEC mooring parameters

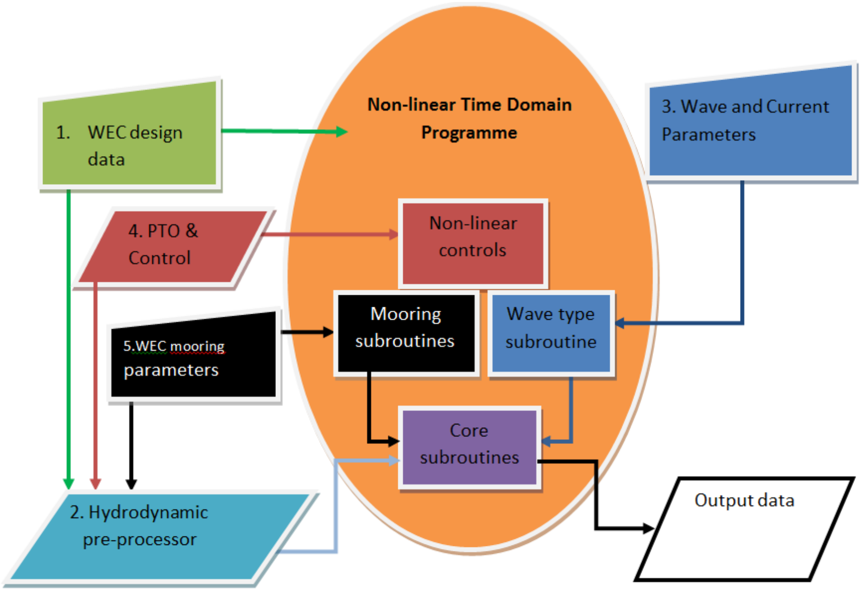


Figure 1 Sketch of a typical W2W model structure

The W2W numerical program

A W2W model integrates the WEC, the forces from the ocean waves, the forces from the PTO and the forces from the mooring system, as schematically presented in Figure 2. To calculate the hydrodynamics associated with the radiation and diffraction of the waves, software such as WAMIT is required (WAMIT, 2012).

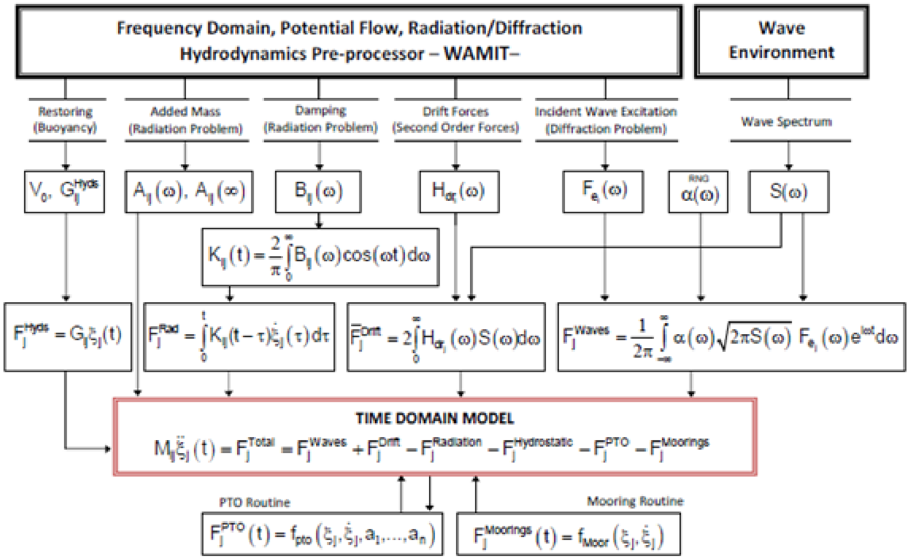


Figure 2 Schematic structure of the W2W model

The numerical W2W model solves the governing differential equations. If these governing equations are *linear*, they can be solved in the *frequency domain* (which is fast) and if the equations are *nonlinear*, the solution can be found in the *time domain*, which in most cases will be slower but will also provide more details.

A global state-space realization can be used, which combines the linear hydrodynamics part with the non-linear parts (the dynamics of the PTO equipment and the mooring system) in order to set up a complete system of Ordinary Differential Equations (ODEs) which describe the entire dynamics of the device. The ODE system is solved by applying a solver using e.g. the Runge-Kutta time-stepping procedure.

For a given input sea condition (which can be zero for the hydrostatics calculations), output data, such as generated electricity, loads and displacements, can be produced.

Table 1: Examples of complete wave2wire codes, their capabilities and features are very different.

	Commercial codes which are solving time domain hydrodynamics online		**Commercial codes based on pre-processed frequency domain BEM hydrodynamics**		**Freeware**
Name of code	DNV GL Sesam HydroD Wasim	Compassis SeaFEM	ANSYS	DNV GL WaveDyn	Do It Yourself with freeware tools
Total price (*1000 €)	15	7	91	47	5
Details	HydroD+Wasim: NOK 118680	SeaFEM+GID USB: 7380€	ANSYS Structural: € 37400 ANSYS AQWA: € 53900	Base module: £ 25000, BEM interface: £ 3000, WAMIT: $24000	Matlab: € 2000 Simulink: € 3000

WEC geometry and design data

The WEC reference design in terms of geometry, dimensions and weights can typically be defined by key data such as:

- *Length*
- *Beam*
- *Draught*
- *Volume*
- *Mass*
- *Center of Buoyancy*
- *Center of Gravity*
- *Moments of inertia*
- *Rated Power*

The geometry is further defined using a CAD drawing. The CAD drawing in i.e. Multisurf, SolidWork or similar, can communicate with the hydrodynamic solver i.e. Wamit or ANSYS – and with the PTO component and mooring component of the W2W model.

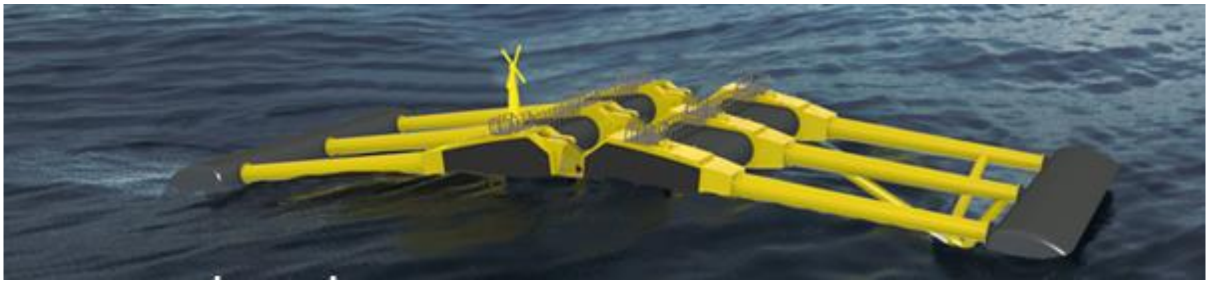


Figure 3 Example of a WEC geometry described in SOLID WORKS

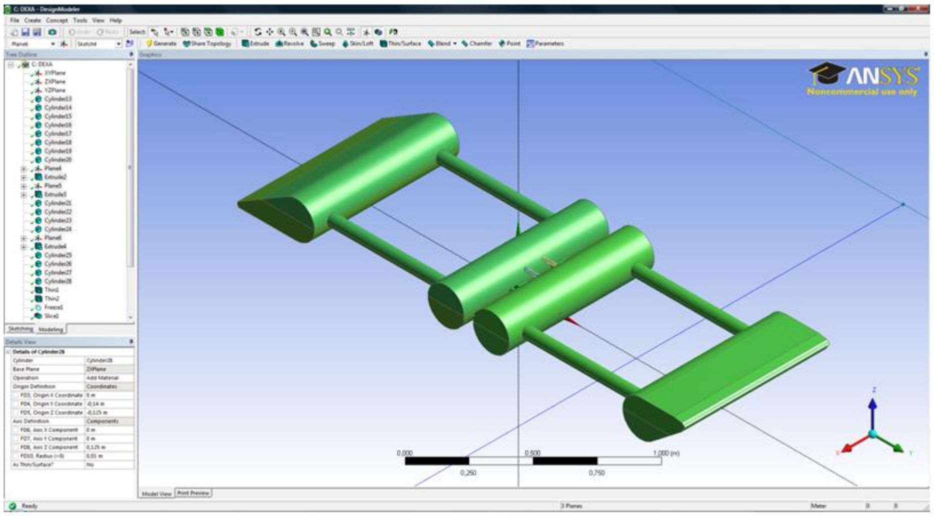


Figure 4 Dexa converter illustrated in ANSYS

Hydrodynamics

The most often referred software that can calculate the hydrodynamic parameters like added-mass, damping coefficients, exciting forces, fluid pressure, fluid velocity and RAOs is WAMIT (WAMIT, 2012). WAMIT implements the linear and second-order potential theory to analyze floating or submerged bodies in ocean waves. The BIEM method (Boundary Integral Equation Method) is used to solve for the velocity potential and fluid pressures on the submerged surfaces of the bodies and simultaneously accounts for the diffraction and radiation effects. There are however other alternatives and some of these are shown in table 2.

Table 2: Examples of hydrodynamic 1st order codes studied within the SDWED project.

	Time domain code	Frequency domain codes			
Name of code	OceanWave3D-SDWED2D	Nemoh	ShipBEM	WAMIT	ANSYS Aqwa
Price for a single user license	Free	Free	N/A	\$24000 ~ €17000	€ 53900

Nemoh is a free alternative to the commercial program WAMIT. It is capable of computing first order wave loads on offshore structures (added mass, radiation damping, diffraction forces). It was developed at Ecole Centrale de Nantes. Since January 2014, it has been released under the terms of the Apache 2 licence. Executables and the source code are available for free download at http://lheea.ec-nantes.fr/doku.php/emo/nemoh/start

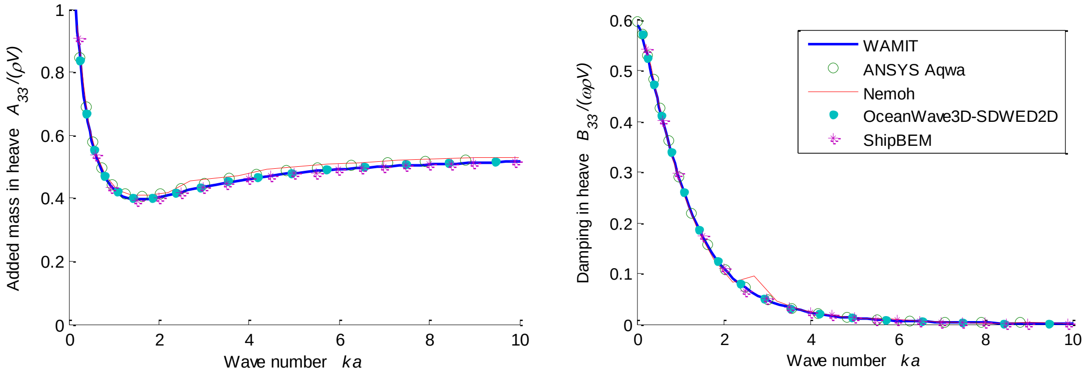


Figure 5 Example of 1st order radiation coefficients for a hemisphere in shallow water $h/a = 2$ (h is water depth, a is radius).

Waves and Current parameters

Regular waves

Typical input is the:

- *Wave Height: H [m]*
- *Wave Period: T [sec]*

Knowledge about the device performance in regular waves is useful mainly because it allows for partial validation of the frequency-domain and time-domain models in relation to model experiments.

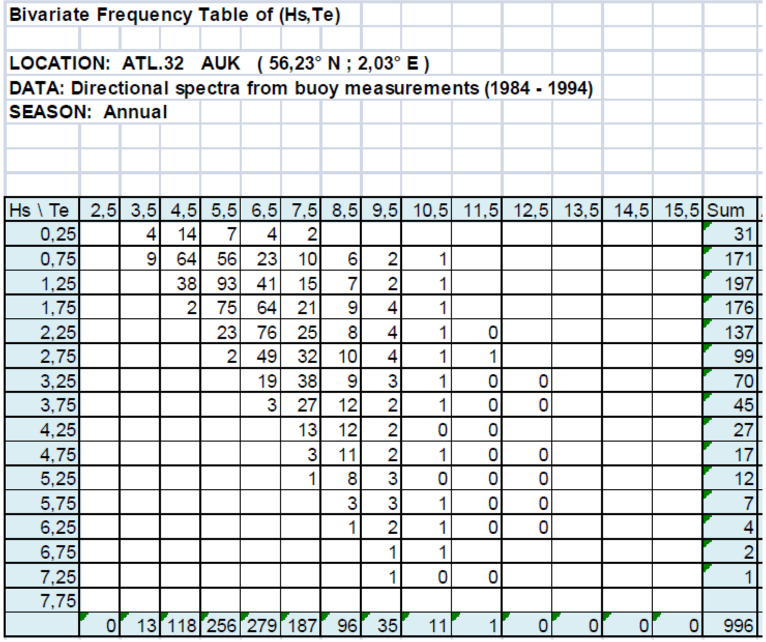
Irregular Sea States

In irregular waves the typical input parameters are:

- *Spectrum type (see Appendix 1)*
- *Significant Wave Height: H_s [m]*
- *Wave Period: T_z or T_e [sec]*

As for regular waves, the evaluation of the loads acting on the device under an irregular sea state also requires the computation of the complex amplitudes of the excitation force (or moment) for unitary incident wave amplitudes. Besides, it is also necessary to specify if the wave elevation time series records of the irregular sea states come from sea measurements or from a stochastic approach.

Typically a scatter diagram presents the frequency per year that each specific sea state occurs, summed up for all directions as shown below:



Bivariate Frequency Table of (Hs,Te)

LOCATION: ATL.32 AUK (56,23° N ; 2,03° E)
DATA: Directional spectra from buoy measurements (1984 - 1994)
SEASON: Annual

Hs \ Te	2,5	3,5	4,5	5,5	6,5	7,5	8,5	9,5	10,5	11,5	12,5	13,5	14,5	15,5	Sum
0,25		4	14	7	4	2									31
0,75		9	64	56	23	10	6	2	1						171
1,25			38	93	41	15	7	2	1						197
1,75			2	75	64	21	9	4	1						176
2,25				23	76	25	8	4	1	0					137
2,75				2	49	32	10	4	1	1					99
3,25					19	38	9	3	1	0	0				70
3,75					3	27	12	2	1	0	0				45
4,25						13	12	2	0	0					27
4,75						3	11	2	1	0	0				17
5,25						1	8	3	0	0	0				12
5,75							3	3	1	0	0				7
6,25							1	2	1	0	0				4
6,75								1	1						2
7,25								1	0	0					1
7,75															
	0	13	118	256	279	187	96	35	11	1	0	0	0	0	996

Figure 6 Scatter diagram for North Atlantic (K. Nielsen & T. Pontes , 2010)

Power Take Off and Control

The part of the wave energy converter that transforms the absorbed power from the waves into electricity to be delivered to the grid is called the Power Take Off (PTO) system.

A classification of typical PTO systems for wave energy systems includes:

- *Direct mechanical/electrical driven systems*
- *Hydraulic systems*
- *Air/Water turbine systems*

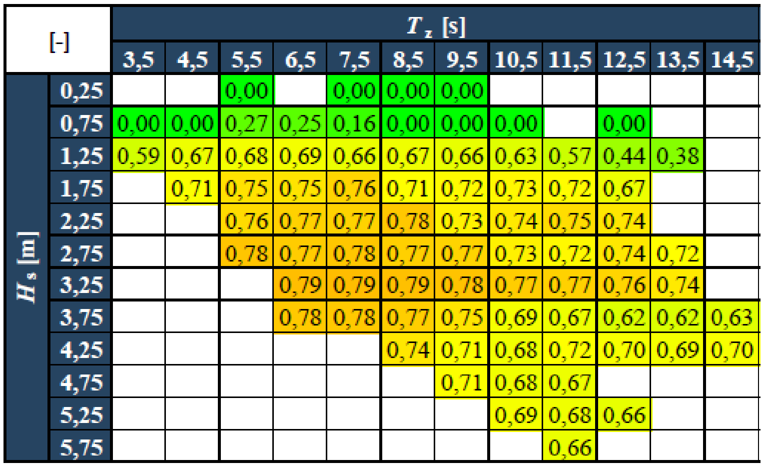
The PTO must deliver electricity that complies with the quality requested by the grid operator. It is at this stage in time not clear which type of PTO system will be the most economical, will be able to convert the wave power to electricity and will survive the ocean environment conditions with a minimum of maintenance.

The numerical model of the PTO can include valves, the fluid, and any other constituent dynamical parts.

The compressibility of the hydraulic fluid can be important, also heating and cooling. For numerical modelling, oil and water hydraulic fluid is considered to be incompressible, whereas the air volume of the OWC systems or gas-accumulators needs to be considered compressible.

There will always be an approximation to the real solution, which results in a compromise between computational effort and solution refinement.

In this way the W2W model can help examine the conversion efficiency of the PTO in the wave situations specified, as shown in the scatter table below.



[-]		T_z [s]											
		3,5	4,5	5,5	6,5	7,5	8,5	9,5	10,5	11,5	12,5	13,5	14,5
H_s [m]	0,25			0,00		0,00	0,00	0,00					
	0,75	0,00	0,00	0,27	0,25	0,16	0,00	0,00	0,00		0,00		
	1,25	0,59	0,67	0,68	0,69	0,66	0,67	0,66	0,63	0,57	0,44	0,38	
	1,75		0,71	0,75	0,75	0,76	0,71	0,72	0,73	0,72	0,67		
	2,25			0,76	0,77	0,77	0,78	0,73	0,74	0,75	0,74		
	2,75			0,78	0,77	0,78	0,77	0,77	0,73	0,72	0,74	0,72	
	3,25				0,79	0,79	0,79	0,78	0,77	0,77	0,76	0,74	
	3,75				0,78	0,78	0,77	0,75	0,69	0,67	0,62	0,62	0,63
	4,25						0,74	0,71	0,68	0,72	0,70	0,69	0,70
	4,75							0,71	0,68	0,67			
	5,25								0,69	0,68	0,66		
	5,75									0,66			

Figure 7 Example of Calculated PTO efficiencies for a hydraulic PTO system (Yukio Kamizuru, Christian Fissmann & Hubertus Murrenhoff, 2013)

Moorings

The moorings keep the floating WEC structure on station (within a certain tolerance) under normal and storm loads, they reduce/remove loads on the electrical connection, they ensure alignment of the wave energy converter and they avoid impact with other structures (ships, etc.). The mooring system needs to be designed to survive extreme loads in storm conditions, which can lead to loads several times higher than operational loads. The mooring system, which is designed with low cost, high reliability, low environmental impact and requiring little inspection and maintenance, plays a very important role for the success of wave energy devices.

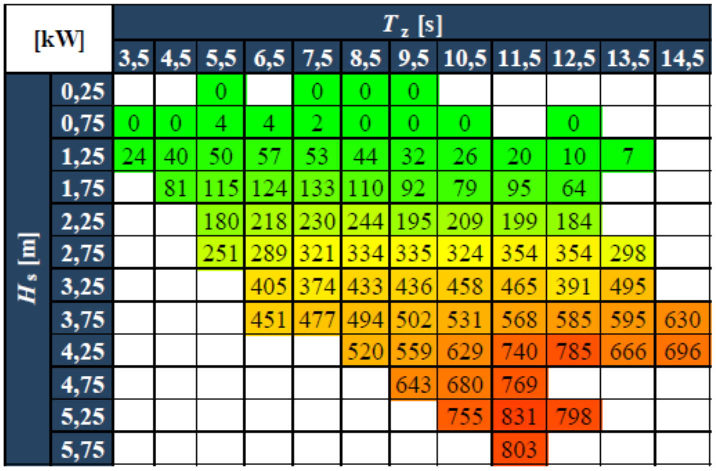
Typically the mooring geometry must be specified in terms of:

- *Number of anchors (n)*
- *Anchor points locations (x_n,y_n,z_n)*
- *Stiffness (typical nonlinear)*
- *Weights*
- *Pretension*

A mooring line can be built using different materials, including floaters and active mooring control in order to achieve the best compromise between cost, reliability and influence on the WEC dynamics. The anchors will not be treated in this context but the loads calculated by the numerical model can help select the appropriate anchor type and dimensions.

Power Output

The prime output produced by the W2W model is illustrated below in terms of a performance matrix that shows the average power output in each cell of the scatter diagram. By combining the performance matrix with the site scatter diagram (Figure 8) the Mean Annual Energy Production can be calculated by summing up the contribution from all cells.



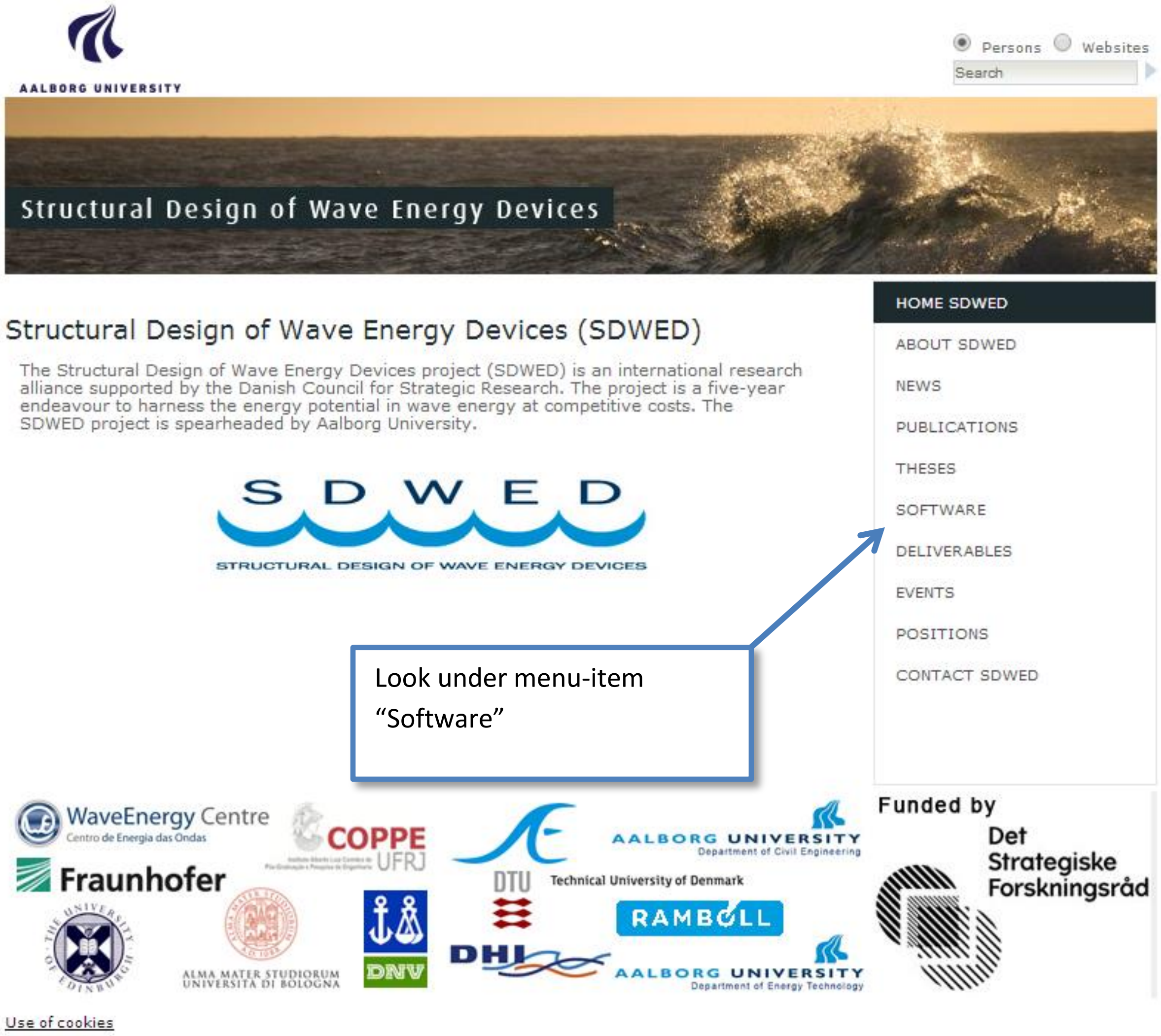
[kW]		T_z [s]											
		3,5	4,5	5,5	6,5	7,5	8,5	9,5	10,5	11,5	12,5	13,5	14,5
H_s [m]	0,25			0		0	0	0					
	0,75	0	0	4	4	2	0	0	0		0		
	1,25	24	40	50	57	53	44	32	26	20	10	7	
	1,75		81	115	124	133	110	92	79	95	64		
	2,25			180	218	230	244	195	209	199	184		
	2,75			251	289	321	334	335	324	354	354	298	
	3,25				405	374	433	436	458	465	391	495	
	3,75				451	477	494	502	531	568	585	595	630
	4,25						520	559	629	740	785	666	696
	4,75							643	680	769			
	5,25								755	831	798		
	5,75									803			

Figure 9 Example of a calculated Power Matrix for a flap type system (Yukio Kamizuru, Christian Fissmann & Hubertus Murrenhoff, 2013)

Tool Overview

A complete overview of the W2W modelling tools available, and particularly developed as part of the SDWED project, can be found on the SDWED webpage under the menu bar “Software”, as shown below.

http://www.sdwed.civil.aau.dk/



Structural Design of Wave Energy Devices (SDWED)

The Structural Design of Wave Energy Devices project (SDWED) is an international research alliance supported by the Danish Council for Strategic Research. The project is a five-year endeavour to harness the energy potential in wave energy at competitive costs. The SDWED project is spearheaded by Aalborg University.

Look under menu-item “Software”

Figure 10 the SDWED webpage 21-05-2014

Appendix 1 Waves

Pierson-Moskowitz Spectrum

The *Pierson-Moskowitz* spectrum is based on the assumption that if the wind blew steadily for a long period and over a large area, the waves would come into equilibrium with the wind, which, basically, is the concept of a *fully developed sea*. Commonly, a long time period is around 10 thousands wave periods, and a large area is roughly 5 thousands wave lengths (see *Pierson* and *Moskowitz*[11]). Thus, the *Pierson-Moskowitz* spectrum, of a fully developed sea, is described by the expression

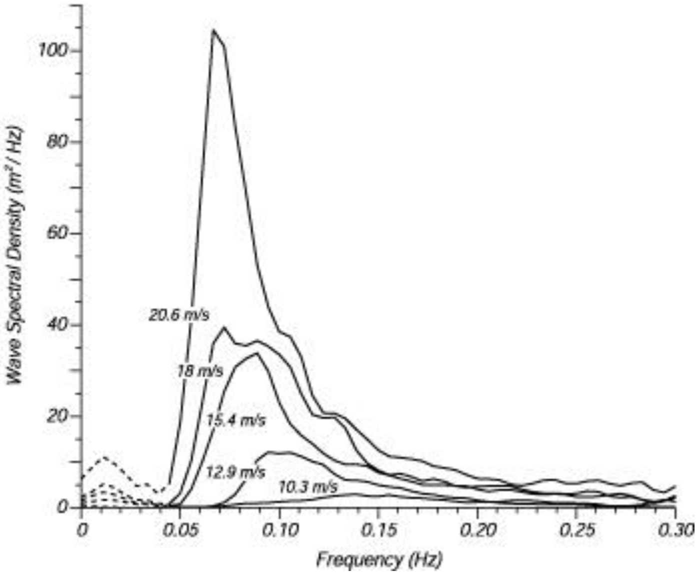


Figure 11 Pierson-Moskowitz fully developed spectrums measured at different wind speeds

$$S(\omega) = \frac{\alpha g^2}{\omega^5} exp\left[-\beta\left(\frac{\omega_0}{\omega}\right)^4\right]$$

The constants involved in this spectrum is gravity g, α=0,0081, β=0,74,

$$\omega_0 = \frac{g}{U_{19.4}}$$

$U_{19.4}$ is the wind speed at an height of 19.4m above the sea surface (19.4m was the height of the anemometers on the weather ships used by *Pierson* and *Moskowitz*[11] in 1964). Generally, for an air flow over the sea $U_{19.5}$=1.026*U_{10} (assuming a drag coefficient of 5.3×10^{-3}), where U_{10} is the wind speed at a height of 10m above the sea surface.

$$H_{1/3} = 0{,}22\frac{(U_{10})^2}{g}$$

Jonswap Spectrum

The *JONSWAP* spectrum formulation has been formulated to fit spectrums that are not fully developed i.e. measured at similar duration and wind speed, at different distances from shore, in the wind's direction (fetch).

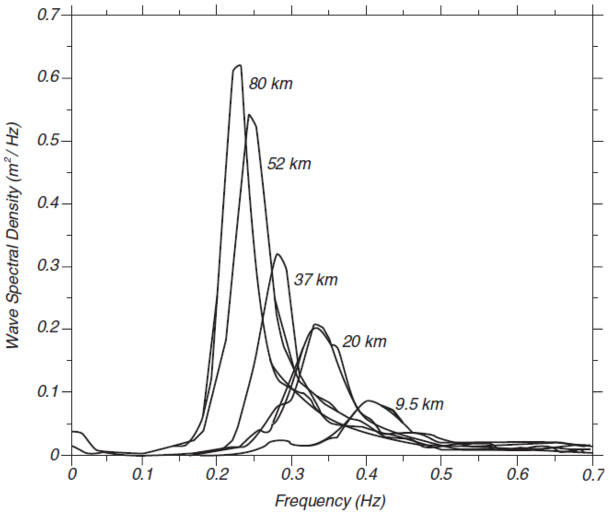


Figure 12 Wave spectra of a developing sea for different fetches measured at JONSWAP. After Hasselmann et al. (1973)

The original expression proposed to describe the *JONSWAP* spectrum contained some inconsistencies. Later, a new expression, proposed by *Hasselmann et al.*[12], attempted to regularize this problem. In accordance with the latter one, the *JONSWAP* spectrum is described by:

$$S(\omega) = \frac{\alpha g^2}{\omega^5} exp\left[-\frac{4}{5}\left(\frac{\omega_p}{\omega}\right)^4\right]\gamma^r$$

The constants included in the above spectrum were determined empirically based on the measurements as

$$\alpha = 0{,}076\left(\frac{U_{10}^2}{Fg}\right)^{0{,}22}$$

$$\omega_p = 22\left(\frac{g^2}{U_{10}F}\right)^{1/3}$$

$$\gamma = 3.3$$

$$\sigma = \begin{cases} 0{,}07 & \omega \leq \omega_p \\ 0{,}09 & \omega \leq \omega_p \end{cases}$$

The constant α corresponds to the Phillips constant of the PM spectrum, but dependent on the fetch F and the wind speed U_{10}. The peak frequency ω_p is also defined related to wind speed U_{10} and *fetch* F.

The constant γ is the relation between the maximum spectral density of the *Pierson-Moskowitz* and *JONSWAP* spectrums.

The parameter σ refers to the semi-length on the left side, σ_a, and right side, σ_b, of the spectral peak.

This shows that the stored energy of the waves increases with the fetch F and the resultant significant wave height, calculated from the *JONSWAP* spectrum, becomes:

$$H_{1/3} = 1{,}63 \times 10^{-3} U_{10} \left(\frac{F}{g}\right)^{1/2}$$

The *JONSWAP* spectrum has a more pronounced peak compared to the *Pierson-Moskowitz* spectrum, which is consistent with the imposed constant γ. The latter turns out to be particularly important because it leads to enhanced non-linear interactions and a spectrum that changes in time, as stated by the theory of *Hasselmann*[12].

Directional Spectrum

Multi-directional random waves can be expressed by a directional spectrum, which may be decomposed into a unidirectional frequency spectrum multiplied by a the directional spreading function or directional distribution.

A spreading function which is often used is given by the following expression:

$$f(\theta) = \begin{cases} A\cos^{2s}(\theta) & for\ |\theta| < \dfrac{\pi}{2} \\ 0 & other\ wise \end{cases}$$

The integral over all directions is unity:

$$\int_0^{2\pi} f(\theta)\, d\theta = 1$$

A large value of the spreading parameter s gives the least spreading. The relationship between the spreading parameter s and the constant A is given by:

$$A = \frac{1}{\pi} \frac{2 \cdot 4 \cdot 6 \cdot \ldots \cdot 2s}{1 \cdot 3 \cdot 5 \cdot \ldots \cdot (2s-1)}$$

Appendix 2 PTO State of the art

In this section is provided a literature review, of the main types of PTO, with a brief explanation of how the PTO works.

Direct Mechanical Drive System

This Direct Mechanical Driven System directly links the electrical generator to the moving parts of the WEC using mechanical connectors. Mechanical connectors can be mooring lines, chain, a gearbox, a pulley, a belt or tooth racks etc . The electricity can be generated using a linear or rotating generator. The velocity fluctuations need to be compensated using storage and frequency converter systems. Storage systems can be battery or electrochemical cells, ultra capacitor and flywheels. All of them have pro and con.

The Uppsala Point Absorber uses a linear electrical generator driven by the relative velocity between the float body and a reference reaction fixed on the seabed (Ivanova, Agren, Bernhoff, & Leijon, 2005), (Ribeiro & Martins, 2010) and (Eriksson, Isberg, & Leijon, 2005).

Hydraulic System

In this class of PTO a hydraulic fluid is used to drive a hydraulic motor that drives a rotating electrical generator. The fluid, which can be either oil or water, is pressurized by hydraulic pistons and delivered either to a hydraulic motor or water turbine driving an electricity generator. This hydraulic PTO can collect hydraulic fluid from several input sources, is able to handle high loads with long periods, is quite a robust and based on well-known components and system. Hydraulic PTO can use storage systems such as gas pressurized accumulators. The hydraulic piston is often a double acting cylinder and a valve loop, i.e. check valves, 4-way directional valves, etc. is used to rectify the flow through the hydraulic motor. This last can be a variable or fixed volume motor or a high-head impulse water turbine, i.e. Pelton type, directly coupled with a rotating generator. Associated with this type of PTO is the need to find solutions for the “end-stop problem”- a solution that ensures that the actuator stays safe within defined limits.

The hydraulic PTO system is used in different application as point absorbers (Wavestar, CPT, AquaBUOY, OPT, Wavebob), attenuator (Pelamis, Dexadevice), terminator (Oyster).

There is much literature concerning the hydraulic PTO published in the last years, (Lasa, Antolin, Angulo, Estensoro, Santos, & Ricci , 2012), (Schlemmer, Fuchsumer, Boemer, Costello, & Villegas, 2011), (Josset, Babarit, & Clement, 2007), (Falcao, 2007) and (Hals, Taghipour, & Moan, 2007). The fluid compressibility is included in all of them, directly or in an artificial way, except for the work carried out by Falcao. A different approach is presented by Costello (Costello, Tingwood, & Weber , 2011), and Kamizuru (Kamizuru, Lermann, & Murrenhoff, 2010), where a direct driven hydraulic motor is used removing the accumulator and controlling the output only in the generator side and finally as referenced in the main text the work by (Yukio Kamizuru, Christian Fissmann & Hubertus Murrenhoff, 2013).

Air Turbine System

Wells air turbines are, beside the hydraulic PTO, the most studied case in literature. Even if the average efficiency of this type of turbine is low, the elimination of moving parts used to rectify the alternate air flow is attractive. Indeed reducing moving part in an offshore system working in high energy location, can increase the working time and reduce the O&M costs.

The most common turbines used are:

- Wells turbine
- Denis-Auld turbine
- Impulse turbine

The turbine is coupled with a high speed rotating generator, which should be able to work at variable speed. In this type of PTO the common way to smooth the power output is basically a combination of flywheel and frequency converter.

Examples of work on Wells turbines are (Cashman, O´Sullivan, Egan, & Hayes, 2009), while (Gareev, 2011) studied a Danniss-Auld turbine. Furthermore in the last year more focus has been reserved into the plant configuration (Alberdi, Amundarain, Garrido, Garrido, Casquero, & De al Sen, 2011) and hybrid system, i.e. offshore wave energy and wind turbine (Aubault, Alves, Sarment, Roddier, & Peiffer, 2011).

Arlitt (Arlitt, Tease, Starzmann, & Lees, 2007) present a work where CFD and dynamical model are coupled, in order to best describe the fluid dynamic around the air turbine. This approach studies the high angle off attach which can lead to stall and energy losses.

Water Turbine Systems

This type of PTO transforms the energy stored in a fluid with high potential energy into mechanical energy, using a water turbine. The literature directly focusing into the wave energy field is relatively small. The power output of the device is then related to the available head and flux. Examples of this type of analysis are (Nielsen K. , On the experimental investigation of a Wave Power Converter, 1985), (Nielsen K. , 1986) (Liu, Hyun, & Jin, 2008), (Iahnke, Gomes, Isoldi, & Rocha, 2010) and (Nam, Shin, & Hong, 2008).

Using seawater hydraulic pumps can produce high pressure heads that can be utilized by Pelton turbines. This has been investigated in the Oyster project as well as the CETO project.

Low head Kaplan or Propeller type water turbines are normally relatively expensive and associated with overtopping type of WECs, i.e. Wave Dragon or SSG where the water is collected into an elevated basin with a head ranging from half a meter to a few meters. The basin water level is a function of sea state and each turbine is coupled with a rotating variable speed generator..

Control

Into the summation of the forces there will be an extra term related with PTO reaction, or feedback, force, while this force will be assess solving the PTO dynamic when the velocity and position of the mechanical interface is given by the prime mover velocity and position.

Appendix 3 Mooring classes description

Basically three classes of mooring configuration are available:

- Spread Mooring
- Single Point Mooring (SPM)
- Dynamic Positioning

Spread Mooring

In this class of mooring configuration several mooring lines are attached to the floating body, normally with a symmetric configuration. Three different subclasses are available, which differ in lines type. This kind of configuration is suitable for non-directional WECs, since the heading angle is fixed with small degree of freedom.

- Catenary Mooring: Mooring line is described in terms of catenary equation, with a U shape. The restoring force is given by the cable/chain weight and the anchor point receives only horizontal loads, due to the line shape. The dynamic of the mooring line can highly affect the WEC dynamic, since an extra weight is acting on it. Since the line reach the anchor point horizontally, a high wear of the material can be possible, due to the friction with the seabed.

- Multi-Catenary Mooring: In this configuration sinkers and floaters are used to create an S-shape or wave shape mooring line, giving a higher degree of freedom and control in the mooring design. The line can be composed by multiple sections of different materials, which will be briefly discussed later. The restoring force is given by the spring term related to the floaters the sinkers and the weight of the mooring line itself. In this configuration the influence onto the dynamic of the floater can be tuned and furthermore, choosing between one of the following lay-out, *Lazy S, Steep S, Lazy Wave, Steep Wave or Pliant Wave*, some control on the angle of attach with the seabed is possible, leading to a reduction of the friction wear of the lines.

- Taut Spread Mooring (Tether mooring): The mooring lines are orthogonal (tension leg platform TLP) or with an angle with respect to the seabed. This means, horizontal and vertical loads on the anchor points. The restoring force is given by the lines elasticity as well as the floater buoyancy.

Single Point Mooring (SPM)

The main different between the first class and this second one is the capability of weathervane around a pivoting point. This allows a load reduction on the structure which can be an economical key parameter. The pivoting point can be either internal or external and provided, or not, with bearing system. Different subclasses are available due to the configuration of the pivoting point.

- Turret Mooring: An internal or external turret, which is catenary moored, acts as a pivoting point. The system is provided with rotational bearing.

- Catenary and Multi-Catenary Mooring: Same concept as spread mooring type, but with only one connection point. It can be rarely a solution due to the high excursion allowed, which is not feasible in farm of WEDs.
- Catenary Anchor Leg Mooring (CALM): The floater is moored to a catenary moored buoy, which act as spring due to the buoyancy variation. The restoring force on the buoy comes from the weight of the catenary lines.
- Single Anchor Leg Mooring (SALM): Same as above, but with only one mooring line between seabed and buoy. This is normally a taut line, which gives the restoring force to the buoy together with it buoyancy.
- Fixed Tower Mooring: The pivoting point given by a rotational bearing mounted on top of a tower fixed to the seabed. This can be a feasible option in case of wind-wave energy farm.

Dynamic Positioning

In this class of mooring, the system actively behaves to keep the floater in position. Due to the high cost this class of system will hardly be a feasible solution.

- Active Mooring: A centenary mooring is used and on board a controller change the length of each mooring line in order to tune the floater to the request condition.
- Propulsion: The positioning of the floater is completely guaranteed by a propulsion system.

State of the Art Numerical Implementation of Moorings

Several examples are available on literature, which couple mooring systems with WEDs or generic floating systems, either in frequency or time domain. The DNV standard (DNV, Position Mooring, OFFSHORE STANDARD, DNV-OS-E301, 2010) gives general guidelines for the design and the mathematical model of a mooring system, defining the different forces acting on the line. Even if is a general point of view this can be good solution if an easy numerical model need to be built, especially if a low computational effort is request in order to simulate long time series for an annual average estimation.

On the other hands, the work carried out by Johanning (Johanning, Smith, & Wolfram, 2007), shows the importance of the damping behavior of the mooring lines due to viscous effects, which in turn define the need of a non-linear time domain model to approximate in a proper way the moored WED.
An example of application of a finite element method coupled either with Morrison’s equation or Diffraction/Radiation problem is reported in (Sagrilo, Siqueira, Ellwanger, Lima, Ferreira, & Mourelle, 2002). The system under investigation is a CALM mooring configuration where the buoy load is obtained using either small body approximation or the diffraction/radiation problem, while the tanker load is obtained using the last one. The mooring dynamic is then assess decomposing the 6 lines in 150 truss non-linear elements solved using the Newmark method. The same approach using linear or slightly non-linear problem for the buoy dynamic response coupled with a finite element method able to analyze the mooring dynamic has been presented by (Chen, Zhang, & Ma, 2001).

A different and more interesting approach has been used by Fitzgerald (Fitzgerald & Bergdahl, 2008), where the non-linear solution has been linearized to create a frequency map of the mooring response.

The map is then applied to the linear unmoored response of the WED, in order to gives a fully linear system. The basic concept of the work is to tune the mooring dynamic coefficient in order to best fit the non-linear behavior. This approach can be seen as a compromise between accuracy and computational time, since after the tuning process obtained using a finite element method, which as a high computational cost; the process can be analyzed in frequency domain, where the computational time is negligible compared with the previous one.

A quasi-static analysis of a multi-catenary mooring based on iterative non-linear solution of the catenary equation is proposed by Yassir (Yassir, Kurian, Indra, & Nabilah, 2010), when different clump weight and pretention are applied. Nevertheless, this procedure can be used until the mooring line remain in a slack configuration, or in other words where the non-linear effect due to viscous damping are considered linear, (Johanning, Smith, & Wolfram, 2007) and (Kreuzer & Wilke, 2003). Furthermore, this last gives a good explanation of the difference between the quasi-static and dynamic approach and examples showing when these two methods converge and when not. The same paper report also the computational cost for the multi-body approach when the number of element change in the system; it is clear that a reported ratio of computational time over real time of 0.1, using the smallest number of element, it is not usable if an annual mean value is the aim of the work.

Same quasi-static approach has been used by Vicente (Vicente, Falcao, & Justino, Slack-chain mooring configuration analysis of a floating wave energy converter, 2011) where the dynamic of a point absorber with an idea reaction plate and PTO is assess for different slack mooring (catenary or multi-catenary SPM) configurations. The importance of this work is the direct application of the method for a wave energy purpose. The proposed method does not take into account any non-linear viscous effect and therefore can underestimate the real effect of the mooring system onto the dynamical response of the WED.

Another interesting work carried out from Vicente (Vicente P. C., Falcao, Gato, & Justino, 2009) is devoted to the analysis of an array of WED. Also in this case the model does not take into account viscous effect but shows a possible reduction of the average power up to 15% when mooring are considered into the array.

Appendix 4 Structural analyses – fatigue

Structural modeling and analysis of wave energy converters includes a modal analysis of its structure. If the load frequency component coincides with the natural frequency of the structure, dynamic amplification can become important and has to be considered in the analysis. In (Tuitman, 2010) it was shown that the hydrodynamic loads may increase significantly by considering the flexibility of a vessel for which the natural period coincides with the period of the waves. Possible software packages which can be used for structural modal and analysis are: ANSYS (Ansys., 2010), ADINA (ADINA, 2012), ABAQUS (ABAQUS, 2012), GeniE (DNV, Sesam GeniE User Manual, 2012), Riflex (Riflex, 2008).

The influence of the Power Take Off system and its control strategy on the structural response may be assumed to have a negative effect regarding fatigue of certain components within the structure. In order to account for forces from a power take off system in a modal analysis it may be recommended to look at the two situations, first the situation where the power take off system is locked (the feedback force is infinitely large) and next where the feedback force is zero, (i.e. a free float situation). The two first natural frequencies from such an analysis will reflect an upper and lower value of the dynamical characteristic of the coupled system i.e. the structural model including power take off forces.

f_n: First natural-frequency of the structural system.

f_p: Peak period of a representative sea spectrum.

- $f_n > f_p$

For such cases the structure can be considered stiff i.e. hydro elastic effects can be neglected and hence, the structural and hydrodynamic model can be treated separately. The hydrodynamic loads are calculated, depending on the geometry of the structure, whether it is large or small compared to the characteristic wavelength. The stress analysis can be performed based on a quasi-static load approach, (ICCS, 2012) and (Wu, 1996). For linear response analysis, fatigue loads may be calculated in the frequency domain by considering a wide band rain flow correction factor.

Wave loads may be calculated by WAMIT (WAMIT, 2012), AQWA (AQWA, 2010) or similar. Some software packages provide an interface utility program to transfer the loads from a Boundary Element Model to a FE Model, namely AQWA (AQWA-WAVE, 2011). However the last task is still subject of ongoing research, (Malenica, 2009) and (Sireta, 2010). A feedback force from a power take off or mooring line system can be considered in the analysis once the hydrodynamic loads are calculated.

- $f_n = f_p$

For structures where the natural frequencies of the dry modes are in the range of the wave frequencies, elastic effects become important. A generalized hydrodynamic mode analysis including the first few structural modes has to be carried out, (Newman J. , 1994). Software packages which can deal with hydrodynamic load analysis based on a diffraction/radiation problem and able to account for deformable structures, are relatively rare. One may often chose to combine different software packages, provided that a functional interface does exist.

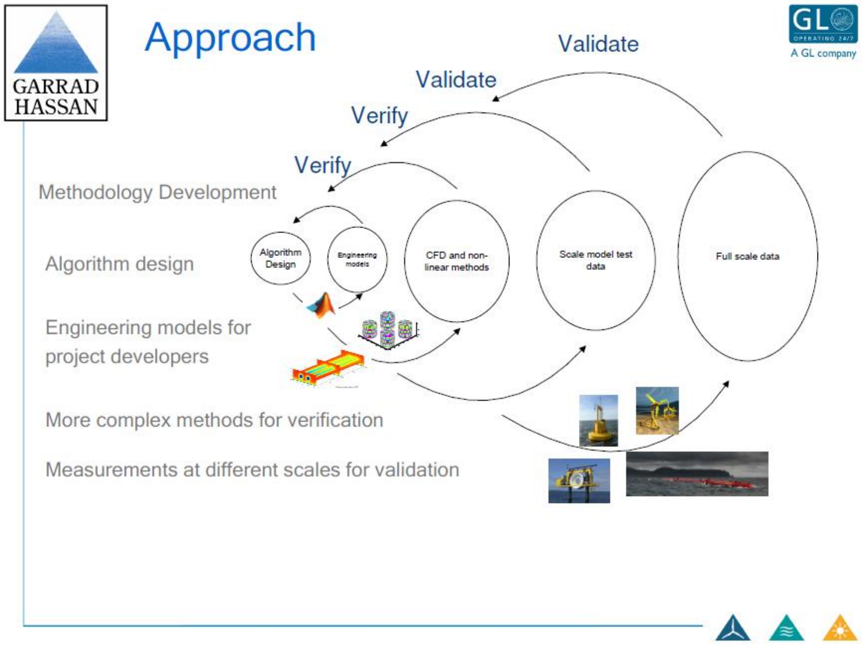
Appendix 5 WaveDyn

The Energy Technology Institute ETI in the UK announced October 2009 their investment of £8m in the project “Performance Assessment of Wave and Tidal Array Systems” (PerAWaT) to be completed at the end of 2013. The Project Partners

- Garrad Hassan
- EDF Energy
- E-ON
- The University of Edinburgh
- University of Oxford
- Queen's University Belfast
- The University of Manchester

The PerAWaT project is producing tools capable of accurately estimating the energy yield of major wave and tidal stream energy converters. Numerical models of devices are being validated using extensive scale model tank testing and full scale data from in-service devices where appropriate.

The project structure and verification and validation of models is described on the presentation[1] from which the figure 2.



Approach

Methodology Development

Algorithm design

Engineering models for
project developers

More complex methods for verification

Measurements at different scales for validation

Figure 13 Approach undertaken by PerAWaT in the development of numerical tools.

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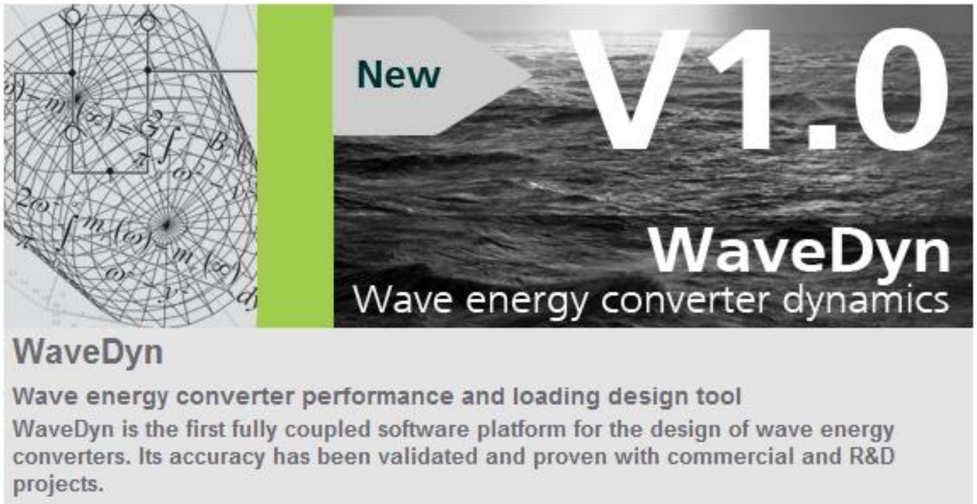
[1] http://www.renewable-uk.com/events/wave-tidal-conference/pdfs/1_Rawlinson_Smith.pdf

GL Garrad Hassan has produced a software tool WaveDyn with outputs from PerAWAT project That was launched in October 2012 (while writing this review) and information on WaveDyn can be obtained at the GL Hassan website[2] and brochure[3]. According to the information on website WaveDyn provides a suitable platform for the accurate design of the widest possible range of wave energy converters, including point absorbers, attenuators, terminators and oscillating wave surge converters.



WaveDyn

Wave energy converter performance and loading design tool

WaveDyn is the first fully coupled software platform for the design of wave energy converters. Its accuracy has been validated and proven with commercial and R&D projects.

Figure 14 State of the W2W model year 2012

WaveDyn supports calculations of combined structural, hydrodynamic and applied loads - such as those induced by power conversion mechanisms (power take-off or PTO) and mooring systems. It is clearly structured with a Windows based graphical user interface. WaveDyn core features include:

- A time-domain simulation environment of combined structural, hydrodynamic and applied loads (e.g. PTO and mooring), with a variable time step integrator for optimization run-times.
- The ability to input a wide range of wave conditions, from measured sea states to parameterized spectral shapes (including directional spectra).
- A multi-body structural dynamics solver, which allows the user to build multi-body structures of different types and forms that match the physical layout of the real machine.
- Accurate and detailed applied forces modules, which allow all the key loads to be fully coupled with the structural model (hydrodynamics, PTO, moorings).
- Nonlinear formulation, including real system templates able to apply motion, force and moment constraints, and incorporate internal PTO states.
- A Windows-graphical user interface with all core pre and post-processing features, and an online help facility.

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[2] http://www.gl-garradhassan.com/en/software/25900.php

[3] http://eti.co.uk/downloads/related_documents/WaveDyn_Brochure.pdf

Bibliography

ABAQUS. (2012). *ABAQUS 6.10 User Manual.* ABAQUS Inc.

ADINA. (2012). *Adina User Manual.* Watertown, MA, USA: ADINA R&D, Inc.

Alberdi, M., Amundarain, M., Garrido, A. J., Garrido, I., Casquero, O., & De al Sen, M. (2011). Complementary control of oscillating water column-based wave energy convertion plants to improve the instantaneous pwoer output. *IEEE, 26*(4), 1021-1032.

Ansys. (2010). *Ansys Mechanical APDL Structural Analysis Guide.* Canonsburg, PA, USA: Ansys, Inc.

AQWA, A. (2010). *ANSYS AQWA User manual.* Canonsburg, PA, USA.: ANSYS, Inc.

AQWA-WAVE. (2011). *AQWA-WAVE User Manual, Hydrodynamic Load Transfer.* West Sussex: Century Dynamics, Limited.

Arlitt, R., Tease, K., Starzmann, R., & Lees, J. (2007). Dynamical system modelling of an oscillating water column palnt based on characteristic curves obtained by computationl fluid dynamics to enhance engineered reliability. Porto: EWTEC.

Aubault, A., Alves, M., Sarment, A., Roddier, D., & Peiffer, A. (2011). Modelling of an oscillating water column on the floating foundation WINDFLOAT. Rotterdam: OMAE.

Brito-Melo, A., & Sarmento, A. (2002). Numerical modelling of a OWC wave-power plants of the oscillating water column type. *Advances In Boundary Element*, 25-34.

Cashman, D. P., O´Sullivan, D. L., Egan, M. G., & Hayes, J. G. (2009). Modelling and Analysis of an Offshore Oscillatin gWater Column Wave Energy Converter. Uppsala: EWTEC.

Chen, X., Zhang, J., & Ma, W. (2001). On dynamic coupling effects between a spar and its mooring lines. *Ocean Engineering, 28*, 863-887.

Costello, R., Tingwood, J. V., & Weber , J. (2011). Comparison of Two Alternative Hydraulic PTO Concepts for Wave Energy Conversion. Southampton: EWTEC.

DNV. (2010). Position Mooring, OFFSHORE STANDARD, DNV-OS-E301. DET NORSKE VERITAS.

DNV. (2012). *Sesam GeniE User Manual.* Oslo: DNV, Managing Risk.

Eriksson, M., Isberg, J., & Leijon, M. (2005). Hydrodynamic modelling of a direct drive wave energy converter. *Journal of engineering science, 43*, 1377-1387.

Falcao, A. F. (2007). Modelling and controll of oscillating-body wave energy converters with hydraulic power take-off and gas accumulator. *Ocean Engineerign, 34*, 2021-2032.

Fitzgerald, J., & Bergdahl, L. (2008). Including moorings in the assessment of a generic offshore wave energy converter: A frequency domain approach. *Marine Structures, 21*, 23-46.

Gao, Z., & Moan, T. (2009). Mooring system analysis of multiple wave energy converters in a farm configuration. Uppsala: EWTEC.

Gareev, A. (2011). Analysis of variable pitch air turbines for oscillating water column (OWC) wave energy converters. University of Wollongong.

Hals, J., Taghipour, R., & Moan, T. (2007). Dynamics of a force-compensated two-body wave energy converter in heave with hydraulic power take-off subject to phase control. Porto: EWTEC.

Harris, R. E., Johanning, L., & Wolfram, J. (2004). Mooring systems for wave energy converters: A review of design issues and choices. *Edinbugh, UK*.

Iahnke, S. L., Gomes, M. N., Isoldi, L. A., & Rocha, L. A. (2010). Energy from the sea, computational modelling of an overtopiing device. Comference of Computational Modelling.

ICCS. (2012). *Quasi-static response.* Hamburg: International Ship and Offshore Structures Congress.

Ivanova, I. A., Agren, O., Bernhoff, H., & Leijon, M. (2005). Simulation of Wave-Energy Converter With Octagonal Linear Generator. *Ocean Engineering, 30*(3), 619-629.

Johanning, L., Smith, G. H., & Wolfram, J. (2007). Measurements of static and dynamic mooring line damping and their importance for floating WEC devices. *Ocean Engineering, 34*, 1918-1934.

Josset, C., Babarit, A., & Clement, A. H. (2007). A wave-to-wire model of the SEAREV wave energy converter. *Journal of Enginnerign for the Maritime Environment, 81*.

K. Nielsen & T. Pontes . (2010). *Report T02-1.1 OES IA Annex II Task 1.2 Generic and Site-related Wave Energy Data.* IEA-OES.

Kamizuru, Y., Lermann, M., & Murrenhoff, H. (2010). Simulation of an ocena wave energy converter using hydraulic transmission. Aachen: International Fluid Power Conference.

Kreuzer, E., & Wilke, U. (2003). Dynamics of mooring systems in ocean engineering. *Applied Mechanics, 73*, 270-281.

Lasa, J., Antolin, J. C., Angulo, C., Estensoro, P., Santos, M., & Ricci , P. (2012). Desing, Construction and testing of a hydraulic power take-off for wave energy converters. *Energies, 5*, 2030-2052.

Liu, Z., Hyun, B.-S., & Jin, J. (2008). Numerical prediction for the overtopping performance of OWEC. *IEEE*.

Malenica, S. S. (2009). Some aspects of hydro-structure coupling for combined action of seakeeping and sloshing. Honolulu: International Conference on Ocean, Offshore and Artic Engineering, OMAE.

Nam, B. W., Shin, S. H., & Hong, K. Y. (2008). Numerical simulation of wave flow over the Spiral-Reef overtopping device. Bangkok: ISOPE.

Newman, J. (1994). Wave effects on deformable bodies. *Applied Ocean Research, 16*, 47-59.

Newman, N. (n.d.).

Nielsen. (2012). *Ocean Energy Technology Study.* DanWEC for GreenOffshore Aliance.

Nielsen, K. (1985). On the experimental investigation of a Wave Power Converter. *UTAM.* Lisbon: Elsvier.

Nielsen, K. (1986). On the Performance of a Wave Power Converter. *International Symposium on Wave Energy.* La Joya: Scripps.

Ribeiro, J., & Martins, I. (2010). Development of a low speed linear generator for use in wave energy converter. Granada: Conference on renewable energy and power quality.

Riflex. (2008). *Riflex Theory Manual.* Trondheim: Marintek.

Sagrilo, L. S., Siqueira, M., Ellwanger, G. B., Lima, E. C., Ferreira, M. D., & Mourelle, M. M. (2002). A coupled approach for dynamic analysis of CALM systems. *Applied Ocean Research, 24*, 47-58.

Schlemmer, K., Fuchsumer, F., Boemer, N., Costello, R., & Villegas, C. (2011). Design and controll of a hydraulic power take-off for an axi-symmetric heaving point absorber. Southampton: EWTEC.

Sireta, F. M. (2010). An efficient hydro structure interface for mixed panel-stick hydrodynamic model. Harbin: 25th IWWWFB.

Tuitman, J. T. (2010). *Hydro-elastic response of ship structures to slamming induced whipping.* Delft: PhD Thesis, Technical University.

Vicente, P. C., Falcao, A. F., & Justino, P. A. (2011). Slack-chain mooring configuration analysis of a floating wave energy converter. iwwwfb.

Vicente, P. C., Falcao, A. F., Gato, L. M., & Justino, P. A. (2009). Dynamics of arrays of floating point-absorber wave energy converters with inter-body and bottom slack-mooring connections. *Applied Ocean Research, 31*, 267-281.

WAMIT. (2012). *WAMIT User Manual.* Chestnut Hill, Massachusetts, USA.: WAMIT Inc.

Wu, M. a. (1996). Linear and Nonlinear Hydroelastic Analysis of High Speed Vessels. *Journal of Ship Research, 40*(2), 149-163.

Yassir, M., Kurian, V., Indra, S., & Nabilah, A. (2010). Parametric Study on Multi-component Catenary Mooring lines for Offshore Floating Structures. Kuala Lumpur: Asian-Pacific-Offshore Conference.

Yukio Kamizuru, Christian Fissmann & Hubertus Murrenhoff. (2013). Hydrostatic Drive Trains for Wave Energy Converters: Simulation and Experiments for Efficient Design. *EWTEC.* Aalborg.