GH Marine

Wave Energy – Device Modelling

Joao Cruz
Wave Energy Team Leader
Whistler, 19th November 2008
OREG 2008 Fall Symposium

Renewable Energy Experts
worldwide

Content

- Introduction to GH
- GH Marine Experience
- Fundamentals of Numerical Modelling
- GH WaveFarmer
- Final Remarks

Who/What is Garrad Hassan?

- Renewable energy consultancy
- Founded in 1984
- Working in 5 continents
- Independent, no equity stake in any project or technology (wind, wave & tidal or solar)

Wind Energy

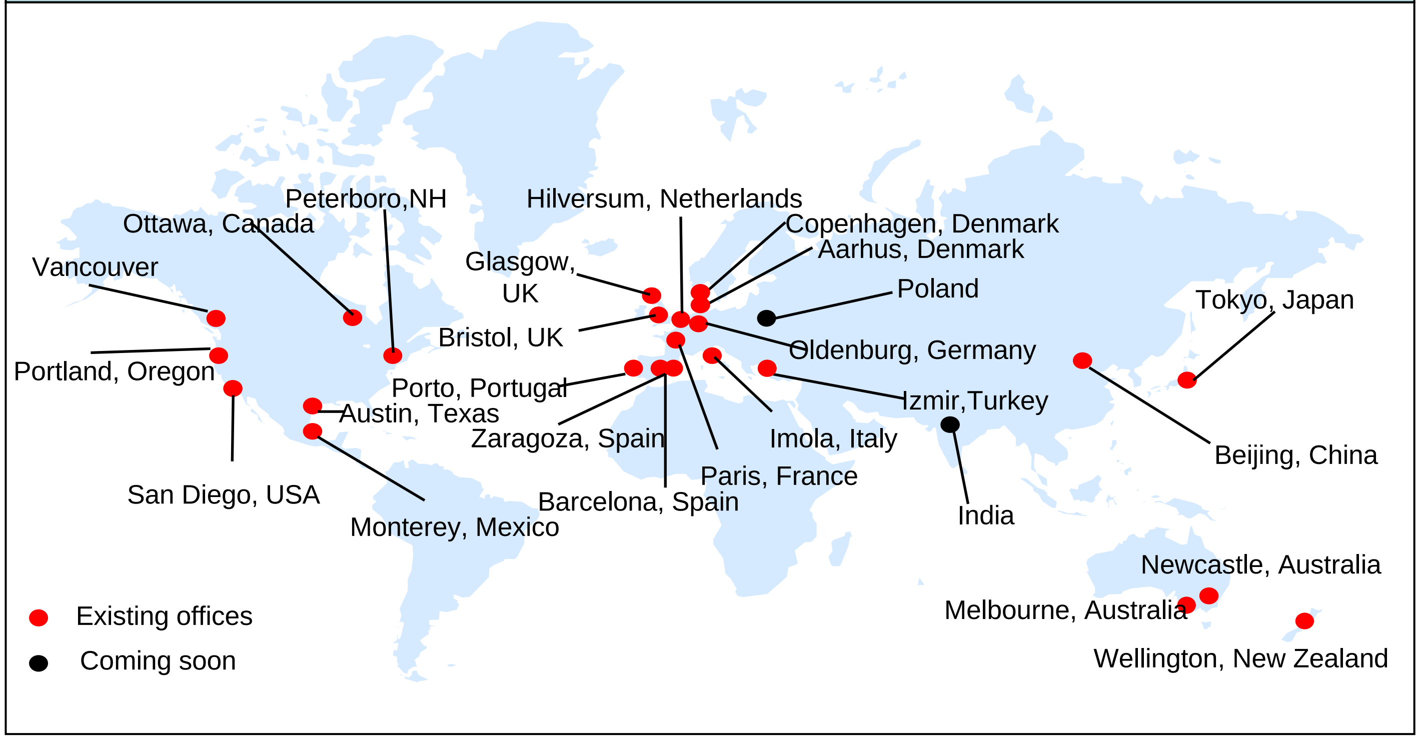
Marine Energy

Solar Energy

Garrad Hassan around the world

- Founded in the UK
- Now have offices worldwide
- Local understanding informs global perspective

300 professionals in 17 countries



Range of GH services - Wind energy

- Wind turbine design, certification and testing services

- Wind farm consultancy services (onshore and offshore)
  - Wind farm design
  - Due diligence
  - Energy assessment – more than 80,000MW to date
  - Independent Engineer – more than 21,000MW operating

- Short term forecasting of energy output

- Research and development

- Industry-standard software supplier

- Strategic services

- Industry training courses
  - **Introduction to Wave Energy Conversion**
    - **Bristol, 1st July**
    - **Whistler, 21st November**

GH Bladed

- Over the past 20 years, GH have played a key role in developing mathematical models of *wind* turbines
- Work resulted in the computer code GH Bladed - acknowledged as a ‘wind industry standard’ design tool
- GH Bladed independently validated by Germanischer Lloyd
- GH Tidal Bladed also available

Certificate

Germanischer Lloyd
WindEnergie GmbH

GL-Wind Certificate No.: ZZ 001A-2003

This Certificate attests that the Computer Code

GH BLADED

developed by
Garrad Hassan and Partners Ltd.
St. Vincent's Works
Silverthorne Lane
Bristol BS 2 OQD
England

has been tested by Germanischer Lloyd WindEnergie GmbH (GL-Wind) since September 1997.

The program GH Bladed, version 3.41a, has been installed on a Pentium 4 PC, 2 GHz under WINDOWS XP. The program has been used in comparative analyses within the certification of different wind turbines. The calculated loads were compared with those from analysis using GL-Wind's own set of aeroelastic programs.

Comparison of results was carried out for

- a 600 kW-class wind turbine with active stall
- a 600 kW-class wind turbine with active pitch
- a 800 kW-class wind turbine with variable speed, stall controlled
- a 1,0 MW-class wind turbine with constant speed, stall controlled
- a 1,5 MW-class wind turbine with variable speed, pitch controlled
- a 2,0 MW-class wind turbine with variable speed, pitch controlled
- a 2,5 MW-class wind turbine with variable speed, pitch controlled

and showed good agreement.

Considering the results it can be stated that the program has been validated for the a.m. wind turbine classes and can be considered a suitable program for the calculation of both onshore and offshore wind turbine loads for design and certification.

Hamburg, 6th February 2003
An/Blun

Germanischer Lloyd
WindEnergie GmbH

ppa. Dr. G. Wacker

i.V. A. Andreä

By DAP German Accreditation System for Testing accredited Certification Body for products
The accreditation is valid for the fields of certification listed in the certificate

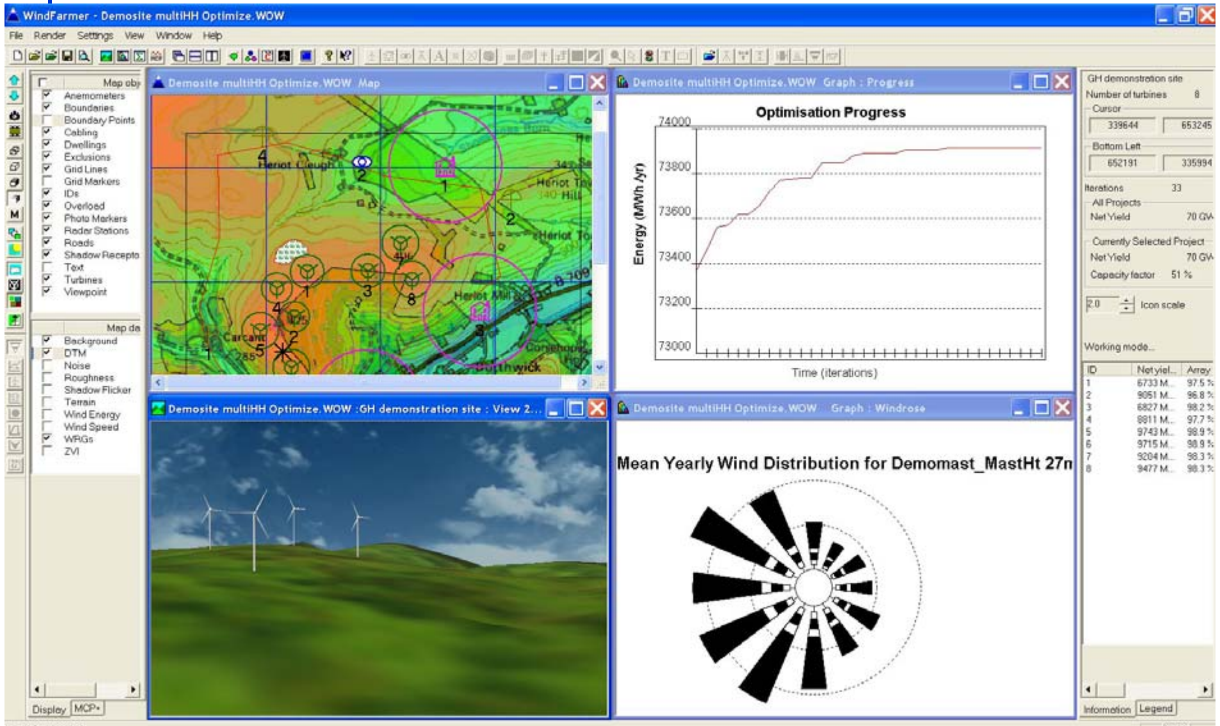
Deutscher Akkreditierungs Rat
DAR
DAP-ZE-3443.00

Germanischer Lloyd WindEnergie GmbH
Johannisbollwerk 6-8
20459 Hamburg
Germany

The latest edition of the "General Terms and Conditions of Germanischer Lloyd WindEnergie GmbH" is applicable. German law applies.

Introducing GH WindFarmer

Software for wind farm design and optimisation



GH demonstration site
Number of turbines 8
Cursor 339644 653245
Bottom Left 652191 335994
Iterations 33
All Projects
Net Yield 70 GW
Currently Selected Project
Net Yield 70 GW
Capacity factor 51 %
2.0 Icon scale
Working mode...

ID	Net yiel...	Array
1	6733 M...	97.5 %
2	9051 M...	96.8 %
3	6827 M...	98.2 %
4	9811 M...	97.7 %
5	9743 M...	98.9 %
6	9715 M...	98.9 %
7	9204 M...	98.3 %
8	9477 M...	98.3 %

- Fully validated software
- Optimises wind farm layout taking account of constraints
- Evaluates energy yield
- Turbulence intensity for loads
- Noise analysis
- Shadow flicker maps
- Design of electrical layout
- Visualisation capabilities
- Financial modelling

Essential for project finance

GH Marine Renewable Services

GH Marine group established in 2005

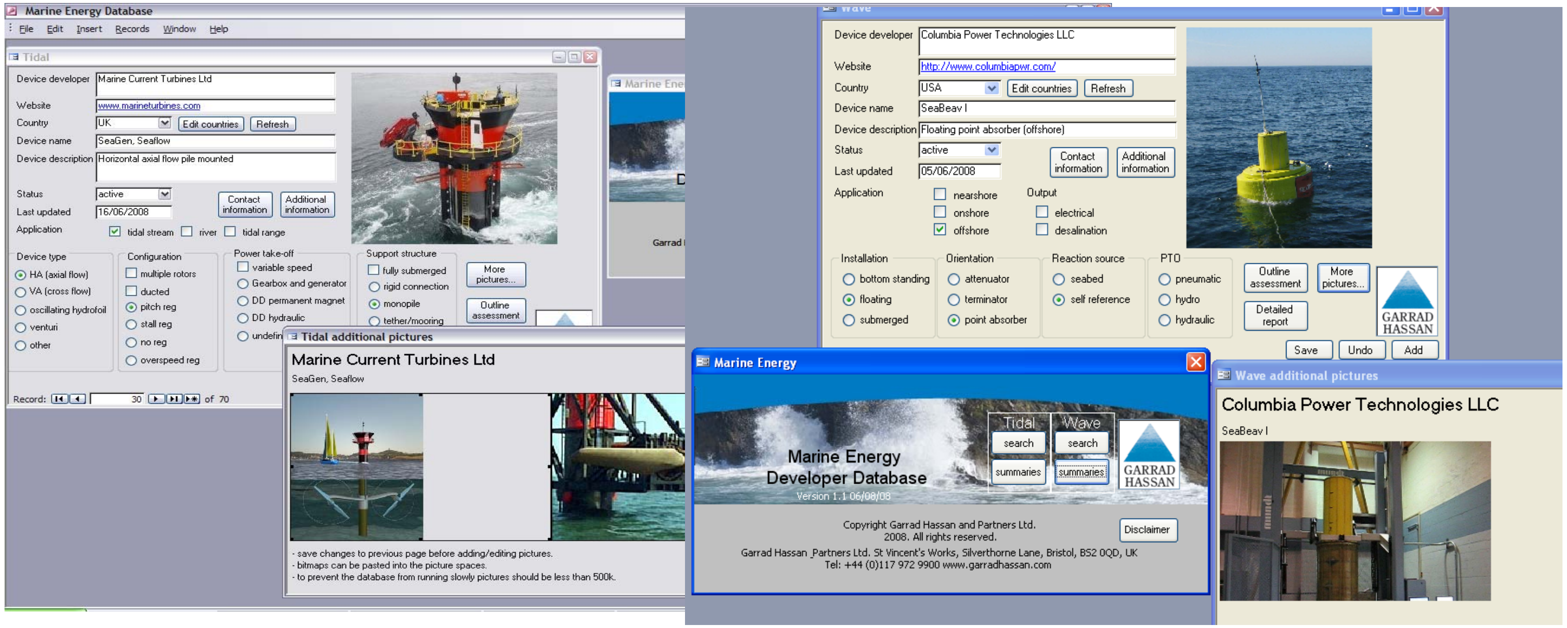
- Resource Assessment
- Technology foresighting
- Technology review and due diligence
- Device modelling
- Control system design
- Market/Commercialisation studies
- Device interaction
- Training courses
- Forecasting

- Strong focus on **R&D**
- Consistent with maturity of the technology

Projects: Wave & Tidal

Technology & Market reviews

- MS Access database of device developers
- Assessment of large number of wave and tidal energy device developers
- Shortlisting of leading developers based on criteria agreed with client
- More detailed review of short listed developers
- Clients include major utilities



Tidal

Device developer: Marine Current Turbines Ltd
Website: www.marineturbines.com
Country: UK
Device name: SeaGen, Seaflow
Device description: Horizontal axial flow pile mounted
Status: active
Last updated: 16/06/2008
Application: ☑ tidal stream ☐ river ☐ tidal range

Device type: ● HA (axial flow) ○ VA (cross flow) ○ oscillating hydrofoil ○ venturi ○ other
Configuration: ☐ multiple rotors ☐ ducted ● pitch reg ○ stall reg ○ no reg ○ overspeed reg
Power take-off: ☐ variable speed ○ Gearbox and generator ○ DD permanent magnet ○ DD hydraulic ○ undefin
Support structure: ☐ fully submerged ○ rigid connection ● monopile ○ tether/mooring

Record: 30 of 70

Tidal additional pictures

Marine Current Turbines Ltd
SeaGen, Seaflow

- save changes to previous page before adding/editing pictures.
- bitmaps can be pasted into the picture spaces.
- to prevent the database from running slowly pictures should be less than 500k.

Wave

Device developer: Columbia Power Technologies LLC
Website: http://www.columbiapwr.com/
Country: USA
Device name: SeaBeav I
Device description: Floating point absorber (offshore)
Status: active
Last updated: 05/06/2008
Application: ☐ nearshore ☐ onshore ☑ offshore
Output: ☐ electrical ☐ desalination

Installation: ○ bottom standing ● floating ○ submerged
Orientation: ○ attenuator ○ terminator ● point absorber
Reaction source: ○ seabed ● self reference
PTO: ○ pneumatic ○ hydro ○ hydraulic

Marine Energy

Marine Energy Developer Database
Version 1.1 06/08/08

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Tel: +44 (0)117 972 9900 www.garradhassan.com

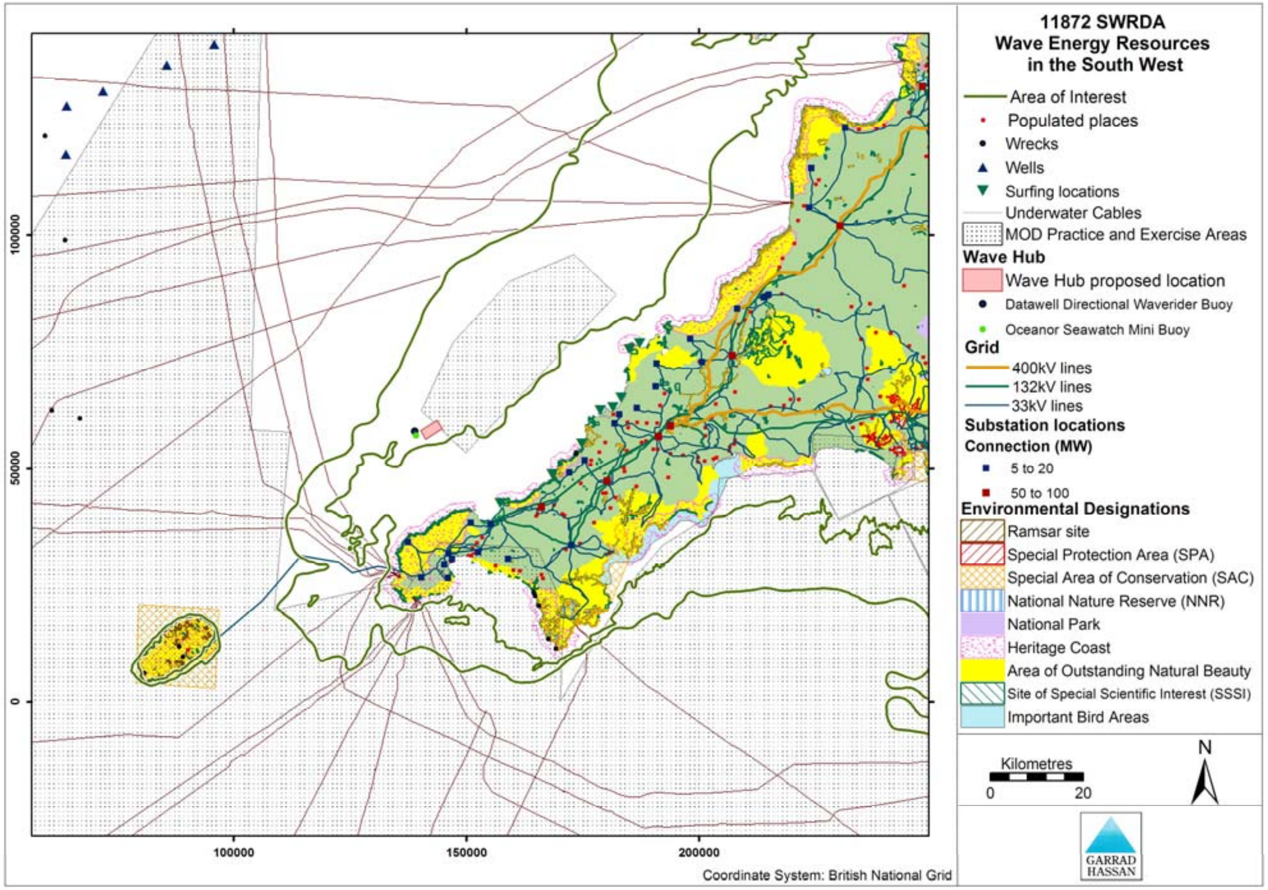
Wave additional pictures

Columbia Power Technologies LLC
SeaBeav I

Projects: Wave Energy

Site and zone selection studies

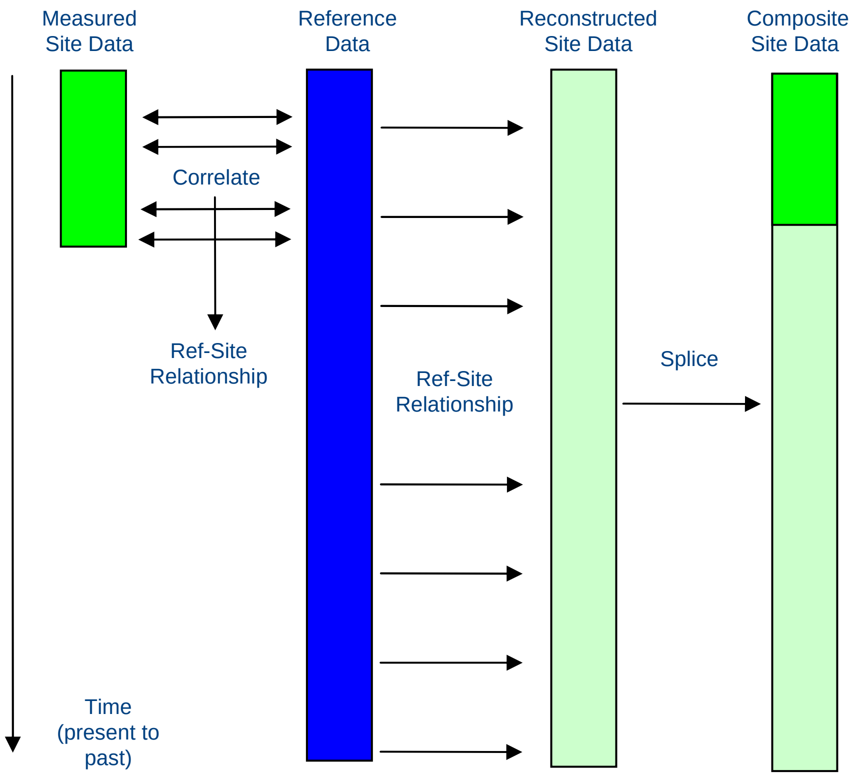
- Country specific GIS database of energy resource and key constraints
- Creation of country specific marine energy atlases
- Clients include project developers and banks



Projects: Wave Energy

Npower Juice fund: Wave Hub Project

- 3 strands: Long-term wave climate characterisation, Forecasting, O&M modelling
- Successful application of the MCP methodology
- Emulation of the GH O2M tool



Measured Site Data

Reference Data

Reconstructed Site Data

Composite Site Data

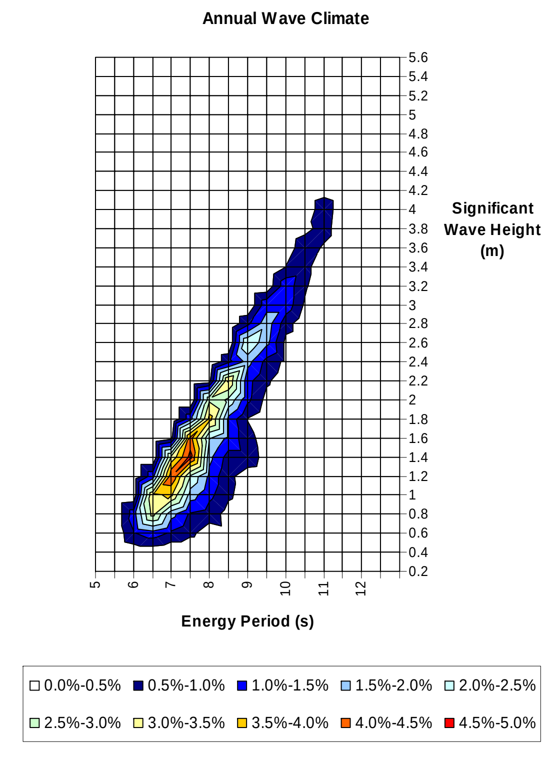
Correlate

Ref-Site Relationship

Ref-Site Relationship

Splice

Time (present to past)



Projects: Wave Energy

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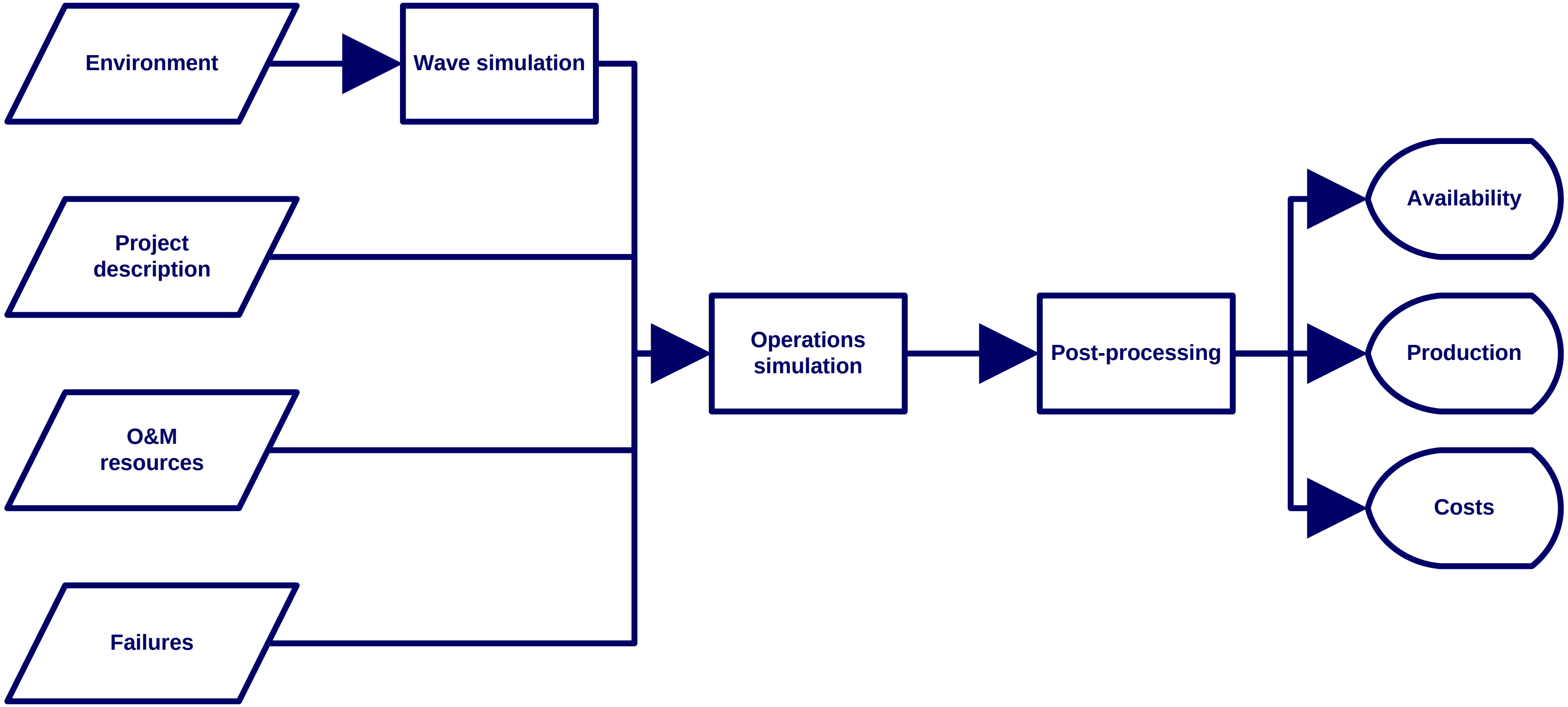
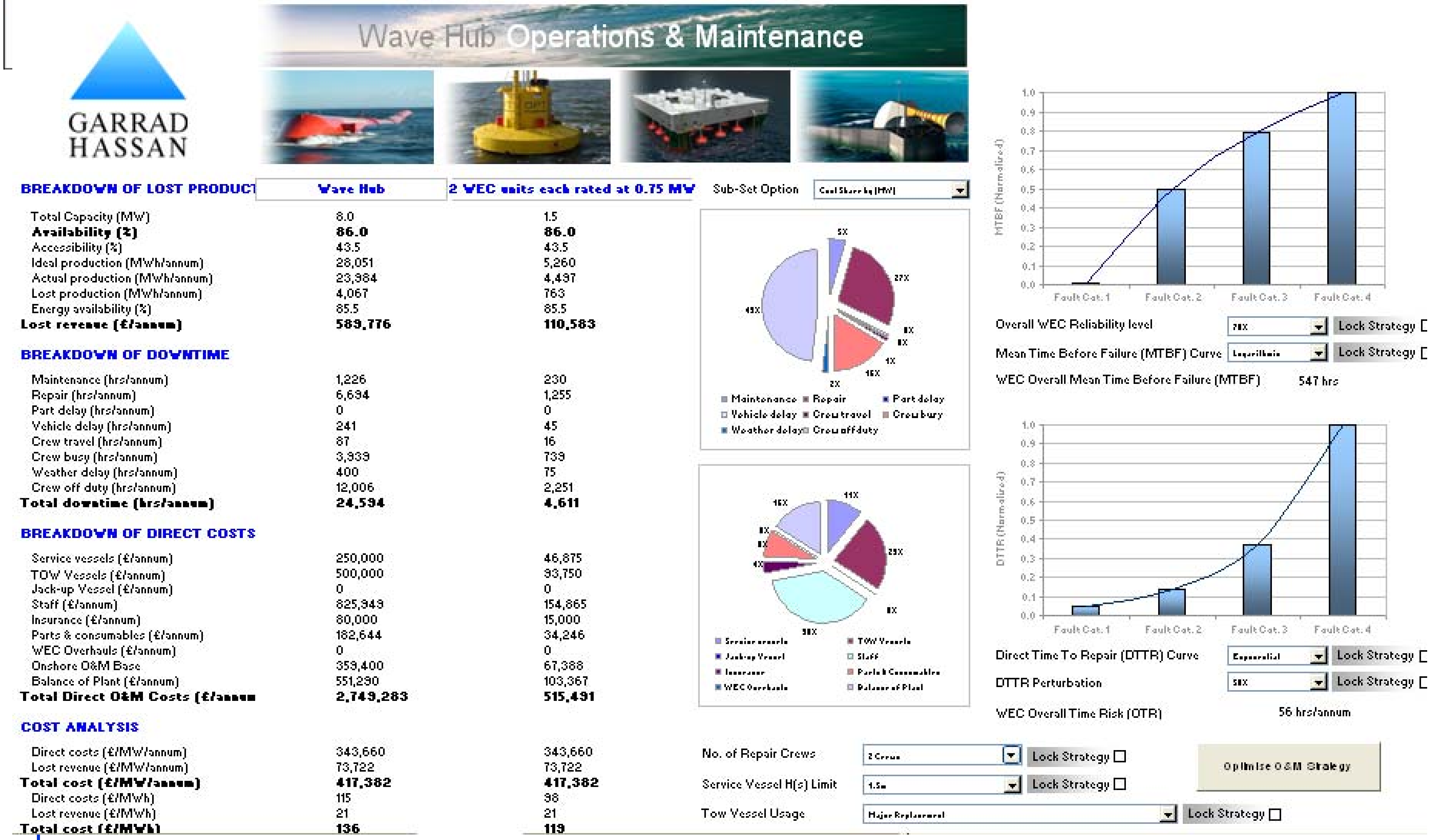


Projects: Wave Energy



BREAKDOWN OF LOST PRODUCT	Wave Hub	2 WEC units each rated at 0.75 MW
Total Capacity (MW)	8.0	1.5
Availability (%)	**86.0**	**86.0**
Accessibility (%)	43.5	43.5
Ideal production (MWh/annum)	28,051	5,260
Actual production (MWh/annum)	23,984	4,497
Lost production (MWh/annum)	4,067	763
Energy availability (%)	85.5	85.5
Lost revenue (£/annum)	**589,776**	**110,583**
BREAKDOWN OF DOWNTIME		
Maintenance (hrs/annum)	1,226	230
Repair (hrs/annum)	6,694	1,255
Part delay (hrs/annum)	0	0
Vehicle delay (hrs/annum)	241	45
Crew travel (hrs/annum)	87	16
Crew busy (hrs/annum)	3,939	739
Weather delay (hrs/annum)	400	75
Crew off duty (hrs/annum)	12,006	2,251
Total downtime (hrs/annum)	**24,594**	**4,611**
BREAKDOWN OF DIRECT COSTS		
Service vessels (£/annum)	250,000	46,875
TOW Vessels (£/annum)	500,000	93,750
Jack-up Vessel (£/annum)	0	0
Staff (£/annum)	825,949	154,865
Insurance (£/annum)	80,000	15,000
Parts & consumables (£/annum)	182,644	34,246
WEC Overhauls (£/annum)	0	0
Onshore O&M Base	359,400	67,388
Balance of Plant (£/annum)	551,290	103,367
Total Direct O&M Costs (£/annum	**2,749,283**	**515,491**
COST ANALYSIS		
Direct costs (£/MW/annum)	343,660	343,660
Lost revenue (£/MW/annum)	73,722	73,722
Total cost (£/MW/annum)	**417,382**	**417,382**
Direct costs (£/MWh)	115	98
Lost revenue (£/MWh)	21	21
Total cost (£/MWh)	**136**	**119**

Sub-Set Option: Cost Share by (MW)

Overall WEC Reliability level: 70% — Lock Strategy ☐
Mean Time Before Failure (MTBF) Curve: Logarithmic — Lock Strategy ☐
WEC Overall Mean Time Before Failure (MTBF): 547 hrs

Direct Time To Repair (DTTR) Curve: Exponential — Lock Strategy ☐
DTTR Perturbation: 50% — Lock Strategy ☐
WEC Overall Time Risk (OTR): 56 hrs/annum

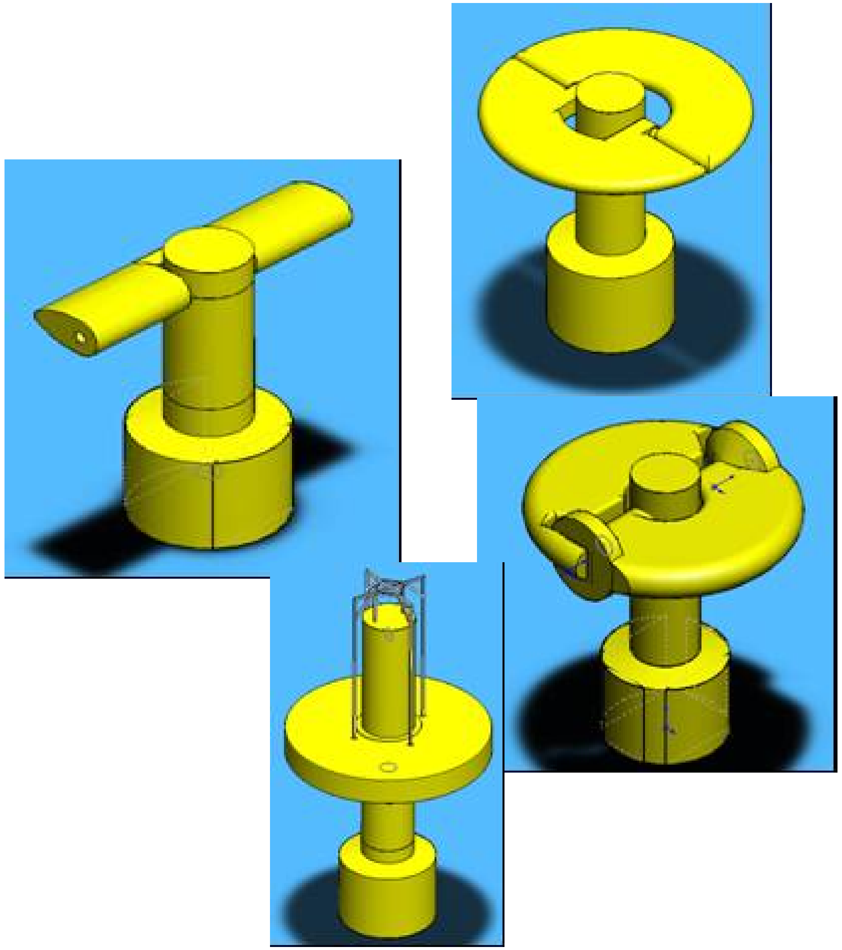
No. of Repair Crews: 2 Crews — Lock Strategy ☐
Service Vessel H(s) Limit: 1.5m — Lock Strategy ☐
Tow Vessel Usage: Major Replacement — Lock Strategy ☐

Projects: Wave energy

Contracts with device developers:

- numerical modelling (frequency and time domain)
- experimental testing
- certification support
- full scale deployment

Numerical simulations conducted in the first modules of **GH WaveFarmer**



GH WaveFarmer

- **Frequency domain modelling (GH FD)**
  - Hydrodynamic coefficients
  - Excitation forces
  - Response Amplitude Operator (RAO)
  - Multiple body interactions
  - Drift forces
  - Regular / irregular waves
  - Geometry / configuration optimisation under optimal control settings

- **Time domain modelling (GH TD)**
  - Irregular waves
  - Real wave spectra input (leading to site specific power matrices)
  - Nonlinear hydrodynamics (analysis of extreme events)
  - Body motions
  - Mooring design / influence
  - Nonlinear power take-off characteristics
  - Custom control strategies
  - Multiple body interactions (wave farm design)

GH WaveFarmer

- **Wave analysis (GH Waves)**
  - Input from several sensors (SEAWATCH, Waveriders, ADCPs, etc)
  - Quality check
  - Key spectral parameters
  - Directional spectrum estimation
  - Extreme event analysis
  - Long-term resource assessment (via numerical and field data)
  - MCP (site specific bankable resource)
  - GIS capabilities
  - Modelling of local effects (bathymetry, shallow water effects, hotspots)
  - Link to Time Domain module

- **Monitoring (GH WaveFarmer Supervisor)**
  - Link to GH SCADA
  - Joint monitoring of wave and machine data
  - O&M planning (emulation of the O2M package), including weather window forecasting (emulation of the GH Forecaster package)

Fundamentals of Numerical Modelling

Key Steps:

- Engineering design
- **Theoretical/numerical modelling**
- Validation in wave basin/flume
- Engineering & prototype testing in real sea

Theoretical/numerical modelling

- **First step to assess a given concept/invention**
- **Essential to optimize size, geometry of device**
- **Specify/Optimize PTO**
- **Establish control procedures/strategies/algorithms**

Fundamentals of Numerical Modelling

Several potential approaches:

- **Frequency-domain**
- **Time-domain**
- **Stochastic**

Starting point in all cases: linear wave theory

- small amplitude waves and body-motions
- real viscous fluid effects neglected

Nonlinear wave theory may be used at a later stage to investigate other phenomena

Nonlinear forces can be included in the time domain approach (PTO, moorings)

Frequency-Domain Models

Basic assumptions:

- **Monochromatic (sinusoidal) waves**
- **The system (input→output) is linear**

- **Historically the first model**
- **The starting point for the other models**

Advantages:

- **Easy to model and to run**
- **First step in optimization process**
- **Provides insight into device's behaviour**

Disadvantages:

- Poor representation of real waves (monochromatic approach)
- Only a few WECs are approximately linear systems (OWC with Wells turbine)

Time-Domain Models

Basic assumptions:

- **In a given sea state, the waves are represented by a spectral distribution**

Advantages:

- Fairly good representation of real waves
- Applicable to all systems (linear and non-linear)
- Yields time-series of variables
- Adequate for control studies

Disadvantages:

- Computationally demanding and slow to run

Essential at an advanced stage of theoretical modelling

Example: GH WaveFarmer

Typical Scenario:

- Device developer contacts GH with tentative design
- Previous modelling often already conducted
- **GH requested to verify and extend modelling plan**

GH approach

- **GH FD**
  - fundamental hydrodynamic properties
  - device iterations
  - optimisation (unconstrained) and control strategies
- **GH TD**
  - evaluation of different wave climates
  - optimisation under the influence of operational constraints
  - definition of the device power matrix
  - extreme event analysis

Example: GH WaveFarmer

GH FD (Frequency domain):

Basic equation of motion: $m\ddot{x} = f_h(t) + f_m(t)$

h – hydrodynamic

m – mechanically applied

Hydrodynamic force:
$$f_h = \begin{cases} f_d & = \text{diffraction force} \\ f_r & = \text{radiation force} \\ f_{hs} & = -\rho g S x = \text{hydrostatic force} \end{cases}$$

Mechanically applied force: $f_m = -Kx - C\dot{x}$

Linear system (linear spring, linear damper)

Equation of motion: $m\ddot{x} = f_d + f_r - \rho g S x - Kx - C\dot{x}$

Example: GH WaveFarmer

GH FD (Frequency domain):

Equation of motion: $m\ddot{x} = f_d + f_r - \rho g S x - Kx - C\dot{x}$

Solution: $x(t) = X_0 e^{i\omega t}, \quad f_d = F_d e^{i\omega t}, \quad f_r = F_r e^{i\omega t}, \ldots$

$$F_r(\omega) = -A(\omega) - i\omega B(\omega)$$

$A =$ added mass $\quad B =$ radiation damping

A **and** ***B*** **to be computed in a BEM code (GH FD uses WAMIT)**

$$(\underset{\substack{\uparrow\\ \text{mass}}}{m} + \underset{\substack{\uparrow\\ \text{added mass}}}{A})\ddot{x} + (\underset{\substack{\uparrow\\ \text{radiation damping}}}{B} + \underset{\substack{\uparrow\\ \text{PTO damping}}}{C})\dot{x} + (\underset{\substack{\uparrow\\ \text{buoyancy}}}{\rho g S} + \underset{\substack{\uparrow\\ \text{PTO spring}}}{K})x = \underset{\substack{\uparrow\\ \text{Excitation force}}}{F_d} e^{i\omega t}$$

Example: GH WaveFarmer

GH FD (Frequency domain):

Equation of motion: $(m + A)\ddot{x} + (B + C)\dot{x} + (\rho g S + K)x = F_d e^{i\omega t}$

1970's : Falnes, Newman, Evans

- **Optimal power is function of geometry (*A*, *B*) and incident wave (F_d)**
- PTO damping to match hydrodynamic damping
- Control strategy to apply such apply external damping
- 1 DOF optimum: $\bar{P} = \dfrac{1}{8B}\left|F_d\right|^2$

Capture width *L* : measures the power absorbing capability of device (like power coefficient of wind turbines)

$$L = \frac{\bar{P}}{E} \quad \begin{cases} \bar{P} & = \text{absorbed power} \\ E & = \text{power flux of incident wave per unit crest length} \end{cases}$$

Example: GH WaveFarmer

GH FD (Frequency domain):

Equation of motion: $$(m+A)\ddot{x}+(B+C)\dot{x}+(\rho gS+K)x=F_d e^{i\omega t}$$

GH FD iterates on:

- Geometry (added-mass, damping coefficients) and configuration (e.g. ballasting strategy, position of the rotation axis, etc.)
- PTO definition (K,C)
- Control strategy

Key Outputs:

- Diffraction forces, hydrodynamic coefficients
- Drift forces and other outputs relevant for time domain models
- Power absorption characteristics (relative capture width) as function of wave period / frequency

Example: GH WaveFarmer

GH TD (Time Domain):

Equation of motion:

$$(m + \underset{\substack{\uparrow\\ \text{added mass}}}{A_\infty})\,\ddot{x}(t) = \underbrace{\underset{\substack{\uparrow\\ \text{diffraction}}}{f_d(t)} - \underset{\substack{\uparrow\\ \text{hydrostatic}}}{\rho g S\, x(t)} - \underset{\substack{\uparrow\\ \text{radiation}}}{\int_{-\infty}^{t} L(t-\tau)\,\ddot{x}(\tau)\,d\tau} + \underset{\substack{\uparrow\\ \text{external}}}{f_m(x,\dot{x},t)}}_{\text{forces}}$$

$$L(t) = \frac{1}{2\pi}\int_0^\infty \frac{B(\omega)}{\omega}\sin\omega t\, d\omega$$

memory function: influence that a change in the momentum of the fluid (at t = ti) will have at t > ti. For stationary structures (zero forward speed) such function depends exclusively on the geometry of the body

$$f_d(t) = \sum_n f_{d,n}(t)$$

diffraction force: from spectral distribution (e.g. Pierson-Moskowitz)

Example: GH WaveFarmer

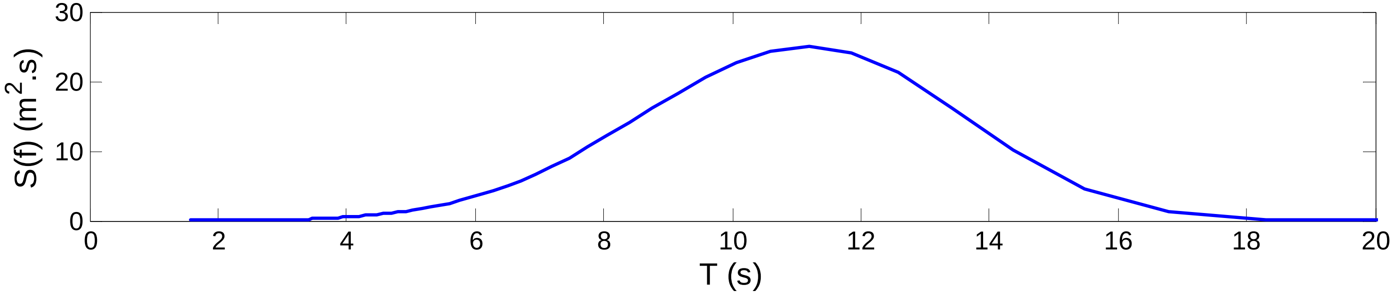
GH TD (Time Domain):

1) Selection of Spectrum: Real (GH Waves) or Modulated (PM, Bretschneider, JONSWAP)
2) If using modulated spectra: define spectral parameters (minimum: H_{m0})

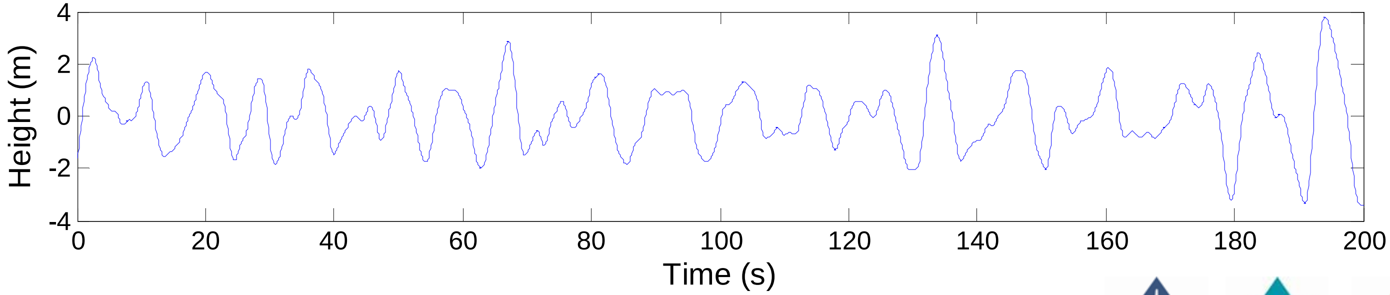
Outputs

- **wave amplitude vs. freq. (relevant for RAO spectra, F_d spectra)**
- **free surface elevation (wave height vs. time)**
- **Extension for modulated seas: directional spreading**

Variance Density Spectrum - PM

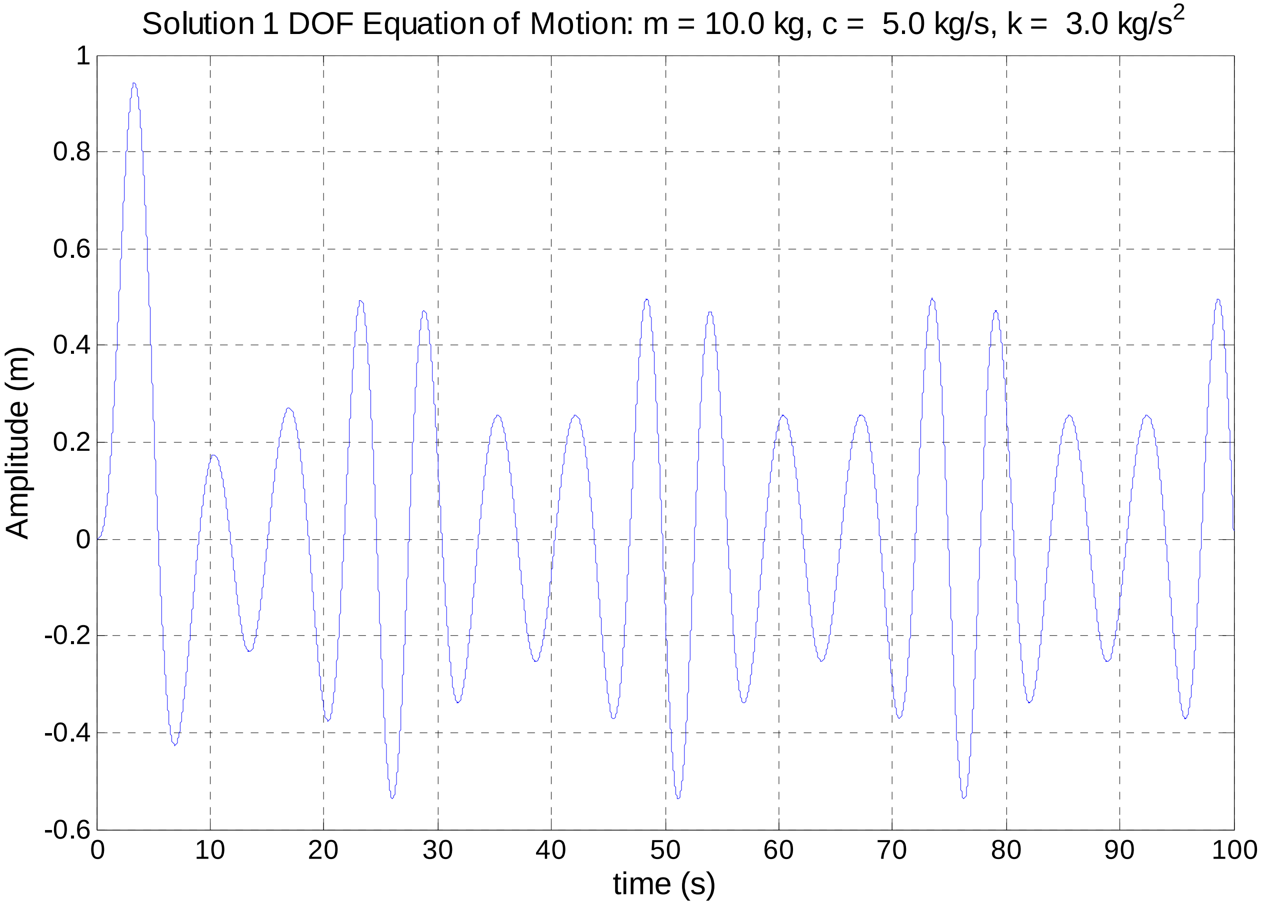


Sea State



Example: GH WaveFarmer

$$(m + A_\infty)\ddot{x}(t) = f_d(t) - \rho g S\, x(t) - \int_{-\infty}^{t} L(t-\tau)\ddot{x}(\tau)\, d\tau + f_m(x, \dot{x}, t)$$



Example: GH WaveFarmer

$$(m + A_\infty)\ddot{x}(t) = f_d(t) - \rho g S\, x(t) - \int_{-\infty}^{t} L(t-\tau)\ddot{x}(\tau)\, d\tau + f_m(x, \dot{x}, t)$$

GH TD iterates on:

- Sea states – real (site specific) or user defined (representative / target markets)
- PTO definition
- Control strategy
- Operational constraints (e.g. motion / velocity limitations)

Key Outputs:

- Time domain solution of the equation(s) of motion
- Influence of realistic (non-linear) external constraints (PTO and mooring forces)
- Site specific power matrices
- Extreme event analysis

Final Remarks

- Hydrodynamic modelling (both frequency and time domain) has been used in the offshore industry over the last decades
- There are clear similarities with the wave energy conversion problem:
  - Same theoretical principles;
  - Same need for experimental validation (in particular for nonlinear / extreme events).
- Currently there is no commercially available software to handle the specific issues of modelling numerically a WEC (coupled influence of hydrodynamics of N bodies locked in M modes along with PTO, control, moorings, …)
- GH WaveFarmer is currently available as a service and will follow GH WindFarmer's steps to become a product
- In addition to the topics described in this presentation, and as the name suggests, GH WaveFarmer will handle farm effects such as:
  - Influence of the sea state in farm elements (wave propagation);
  - Influence of incident / radiated / diffracted wave fields between elements (constructive / destructive interference) – farm control;
  - Layout optimisation (energy yield) as function of the above and additional relevant constraints (e.g. moorings, access routes)

Thank you!

Intro Wave Energy Conversion Course, Whistler, 21st Oct

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