Mathematical Tools in the Design of Floating Devices for Energy Exploitation in Marine Environment

Vincenzo Nava
Imanol Touzon Gonzalez
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Design of Floating Devices: An Operational Perspective

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Moorings And Aero-HydroElasticity Issues
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Energy Conversion

Grid Integration and Power Quality

Conclusions
Tecnalia is a no-profit private technological corporation, arising from the Basque business environment.

Now it is an International benchmark in several field of expertise. We all share a common operating model based on sector-focused Business Units

Generating GDP connecting scientific, applied and technological research.
To turn energy and environmental challenges into business opportunities

- Renewable Energies
- Smart Grids
- Energy Storage and Electric Mobility
- Marine Energy
- Solar Energy
- Biorefinery and Bioenergy
- Energy Efficiency
- New Materials for a Low Carbon Economy
- Clearing up Uncertainties Related to Weather and Climate
- Sustainable and Resilient Cities and Territories
- Forecasting Systems
- Water Cycle
- Efficient Use of Resources
- Waste Valorisation

Energy and Environment

Future Energy System

Sustainability as Megatendency
New concepts for **high power electric generators**.

**Reliable power converters** based on advanced topologies and new devices.

**Structural materials** for blades.

**Hydrodynamic analysis** and performance of WEC

Design of **moorings** systems and **umbilical** cables.

Power **converters** and **control systems**

**Dynamic models** for performance assessment and grid integration

**Materials** for Marine Environment

**Environmental Impact Studies**

**Site** assessment and **resource** characterization

**Grid connection** of marine renewable parks
Renewable Energy in Marine Environment

- *Sea as Resource*
  - Gradients of Salinity
  - Temperature
  - Tides and Currents
  - Ocean Waves

- *Sea as Environment*
  - Marine Geothermal
  - Marine Biomass
  - Offshore Wind
  - Other sources
MARINE RENEWABLE ENERGIES AND DEVELOPMENT OF FLOATING DEVICE TECHNOLOGIES

Waves and Offshore wind may represent the most convenient choices to invest, despite the unavoidable technological and economic challenges of the sectors:

- Efforts distributed in a variety of devices
- Reliability and suitability of the conversion
- Hydrodynamic Modelling: energy losses, diffraction/reflection
- Structural Issues (interaction with mooring system)
- Aero-Hydroelasticity (Offshore Wind)
- Survivability
- **Economic feasibility**
MARINE RENEWABLE ENERGIES AND DEVELOPMENT OF FLOATING DEVICE TECHNOLOGIES

Oscillating Water Column (OWC)

Overtopping Devices

Oscillating Bodies (Point Absorbers & Surge Devices)
Platform technologies change with water depth

- Monopile
- Gravity, suction
- Tripod, tripile
- Jacket, truss
- Semisub, spar, tension leg

Platform cost vs. water depth:
- Shallow water technologies
- Transitional technologies
- Floating technologies

BCAM Seminar

Bilbao – 18th October 2013 – Vincenzo Nava
Why “being” **FLOATING**, then?

- Economically *more convenient* for deep water
- It could lead to greater *availability of resource*
- *Reduced visual impact* from seafront
- Seismically *isolated*
- *Reduced risk* due to solitons
- Exploitation of *oil & gas* already consolidated *experience* in conceptual design of the devices (with several differences)
APPROPRIATE MODELING IS MANDATORY
during all the phases of the design process

Mathematical Models hinge upon:

1) *Theories / Practical Considerations*

2) *Empirical Assumptions* (data from developers, previous experience) EXPERIENCE NOT YET MATURE !!!

Mathematical Models must be validated through:

1) *Experimental Testing* EXPENSIVE !!!

2) *Numerical Tools* (Monte Carlo Methods, approaches in time and frequency domains).
A global model for marine energy devices involves multidisciplinary aspects in several fields of engineering:

- Wind/wave climatology
- Hydrodynamics (Fluid-body interaction)
- Aerodynamics
- Electric engineering
- Hydraulics/Mechanics/Turbomachinery
- Structural mechanics
- Electronics
- Cable dynamics

Each of these fields exploits one or more mathematical tools, from statistics to probabilistic methods, perturbative and non perturbative techniques, but also semi-analytical and numerical methods and computational procedures.
Modelling of the environmental input needed as:

1) Design input for the structural design
2) Forecasts in terms of Energy

Characterization of the resources as stochastic process

- Model of the inputs as stationary, ergodic, Gaussian, non Gaussian processes.
- Spectral representation of the input
- Parameterization

**Minimum parameters:**

- $H_{m0}$
- $T_e$
- Energy flux $J$ (kW/m)
Modelling of the environmental input

- Space variability of the inputs:
  - Wave propagation from deep to intermediate and shallow water
  - Wave hindcast models
  - Wind forecasting
Modelling of the environmental input

- Analyses of the inputs

  *Long term and short term statistics of historical data*
  *Probability analyses of the extremes*
DESIGN OF FLOATING DEVICES: AN OPERATIONAL PERSPECTIVE
Hydrodynamics and Dynamics of the Devices subject to Waves

Hydrodynamics and Hydraulics

Dynamics of the structures

Motion of the fluid inside the structure (sloshing phenomena, energy losses)
Loads due to ocean waves can be distinguished into:

• Hydrostatic Loads

• Steady Current Loads

• Wave Loads (Potential Theory)
  - Linear Loads
  - Non Linear Loads (2\textsuperscript{nd} order components)
    - Mean Drift Forces (2nd order components, which however can be calculated from linear potential)
      - Low Frequency Motion (to be included for the study of moored bodies)
      - Higher Frequency Motion (generally neglected in deep water and for floating devices)
  - Non Linear Viscous Effects (due to vortex formation, turbulence, dissipative loads) – Morison Equation
Potential Theory / Linear Approach

Linearization of Navier-Stokes equation, for inviscid, incompressible and irrotational load yields to the existence of a velocity potential function and therefore to *Laplace equation*:

\[ \nabla^2 \Phi = 0 \]

coupled with the boundary conditions:

- On the free surface (z=0):
  \[ \frac{\partial \phi}{\partial z} - \frac{\omega^2}{g} \phi = 0 \]
- On the body surface Sb:
  \[ \frac{\partial \phi}{\partial n} = V \]
- On the seabed (z=-h):
  \[ \frac{\partial \phi}{\partial z} = 0 \]

The solution is generally achieved by separating the potential into different components, respectively incident, diffraction and radiation potential.

\[ \phi = \phi_I + \phi_D + \phi_R \]

- Solution is obtained in an integral form exploiting the results of Green’s Theorem
- Panelization is very important (number, flat panels/lower order methods, curved panels/higher order methods).
Computational Fluid Dynamics

Numerical Solution of the whole Navier Stokes equation, accounting for the full free surface problem.

Computationally demanding.

Really useful for solving specific classes of problems
A full design of a floating offshore wind farm includes numerical models for:

- economical viability;
- stability and hydrodynamics of the platform;
- mooring lines design
- aero-servo-elastic coupling
- structural design (FEM).
High Order Panel Method in Geometry Definition

Direct Solver

Full Diffraction Solution

Heave plate modeled as a dipole
DESIGN OF FLOATING DEVICES: AN OPERATIONAL PERSPECTIVE
Case Study 1: Hydrodynamics of an Offshore Wind Turbine
Mean Drift forces computed by means of Momentum Conservation
Quadratic Transfer Function computed by means of Newman’s approximation
Coupled aero-hydrodynamic models are still at a development stage and are absolutely needed for the development of the offshore wind industry.

Codes (i.e. for example FAST) are being developed taking into account coupled aerodynamics, aero-elasticity and hydrodynamics as response of offshore wind turbines frequently involves structural modes of vibration.

Facts and Challenges:
- Integration of structural modes into a multi-body approach
- Non negligible influence of the mooring lines
- Differences in control system for pitch and blades with respect to fixed turbines
The dynamics can be described by the Cummins Equation:

\[(m + A_\infty)\ddot{x}(t) = F_e(t) - \rho g S x(t) - \int_{-\infty}^{t} K(t - \tau)\dot{x}(\tau) d\tau + F_{\text{ext}}(x, \dot{x}, t)\]

Where \(F_{\text{ext}}\) can represent every non-linear term, including PTO forces, moorings, drag and other terms.

The convolution term represents a radiation memory effect, described by the radiation impulse response function:

\[K(t) = \frac{2}{\pi} \int_{0}^{\infty} B(\omega) \cos(\omega t) d\omega\]

- Realization theory (Hankel SVD)
- Prony method
- Direct Integration

Unless some specific phenomena must be studied, then it is much easier to apply linear solutions (often in the frequency domain) and include nonlinear corrections afterwards!

\[H(\omega) = [M + M_{\text{eq}} + A(\omega)]\omega^2 + [B + B_{\text{eq}} + B(\omega)]j\omega + (K + K_{\text{eq}})\]
INTEGRATION OF ENERGY CONVERSION AND MOORINGS
Moorings And Aero-Hydroelasticity Issues

Analysis and design of the moorings of a floating system

Quasi-Static Approach
— appropriate for mean and low-frequency platform displacements;
— more approximate approach
— higher design safety factors.

Dynamic Approach
— more appropriate for wave-frequency displacements of the platform.
— needs to take into account also hydrodynamic drag forces acting on the mooring line components
— the dynamic analysis must be linearized when coupled with frequency domains analyses
INTEGRATION OF ENERGY CONVERSION AND MOORINGS
Moorings And Aero-Hydroelasticity Issues

Analysis and design of the moorings of a floating system

**Time Domain**

— the effects of non-linear functions of the wave and motion variables can be included.
— equations of motion are solved by direct numerical integration (time consuming)

**Frequency Domain**

— well suited for systems exposed to stationary random loads.
— requires linear equations of motion;
— linearity implies some inaccuracy in effects like drag loads, time varying geometry, variable surface elevation and horizontal restoring forces. However, in many cases these non-linearities can be satisfactorily linearized.
INTEGRATION OF ENERGY CONVERSION AND MOORINGS
Moorings And Aero-Hydroelasticity Issues

Analysis and design of the moorings of a floating system

Pretension=15 kN

<table>
<thead>
<tr>
<th>Pretension (kN)</th>
<th>150 kg/m</th>
<th>450 kg/m</th>
<th>750 kg/m</th>
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<tr>
<td>Horizontal force (N)</td>
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</tbody>
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Offset (m)

-20  0  20  40  60  80  100  120  140
Analysis and design of the moorings of a floating system

System Identification Procedures

The behaviour of the tension at the top of the mooring line is modelled as a dynamic system

\[ \hat{F}(t) = A\ddot{x} + B\dot{x} + Kx \]

Identification of the parameters is achieved by

\[ \left\langle \hat{F}(t)x(t) \right\rangle = \left\langle F(t)x(t) \right\rangle \]

\[ \left\langle \hat{F}(t)\dot{x}(t) \right\rangle = \left\langle F(t)\dot{x}(t) \right\rangle \]

Principle of conservation of energy

Or LSQ methods
INTEGRATION OF ENERGY CONVERSION AND MOORINGS
Case Study 2: System Identification for Characterization of Moorings

Analysis and design of the moorings of a floating system

System Identification Procedures

![Graph 1](image1)

![Graph 2](image2)
INTEGRATION OF ENERGY CONVERSION AND MOORINGS
Case Study 2: System Identification for Characterization of Moorings

Analysis and design of the moorings of a floating system

System Identification Procedures
The problem of control

Optimization of power absorption

CONTROL SYSTEM

REAL – TIME CONTROL
i. Change the phase of the motion of the body continuously
ii. Time domain analysis required

SEA – STATE CONTROL
i. The control law is changed in correspondence of the sea state
ii. Frequency domain analysis required
Linear Power Take Off Modelling: **PM Synchronous Linear Generator**

Can be approximated by a linear damping coefficient in the Equation of Motion

**Design and model of a hydraulic PTO**
DESIGN OF FLOATING DEVICES: AN OPERATIONAL PERSPECTIVE
Grid Integration and Power Quality Issues

- Stochastic nature of the resource
- Strength of the grid
- Numerical Modelling for Power Quality Issues
- Efficient transport and control
CONCLUSIONS

Numerical and mathematical modelling is a mandatory step in any engineering design process.

Models serve to
- describe the reality more or less reliably
- allow scientists to understand phenomena, their implication and their causes
- provide to the designers powerful tools for the assessment of their objectives.

Importance of good modelling is increased especially when experience is not mature yet, as in the field of renewable in marine environment, especially when dealing with floating devices for wind and wave energy harvesting.

The appropriateness of these models may result in the success or failure of a concept or idea.
Thank you!

Vincenzo Nava
TECNALIA – Marine Energy
vincenzo.nava@tecnalia.com