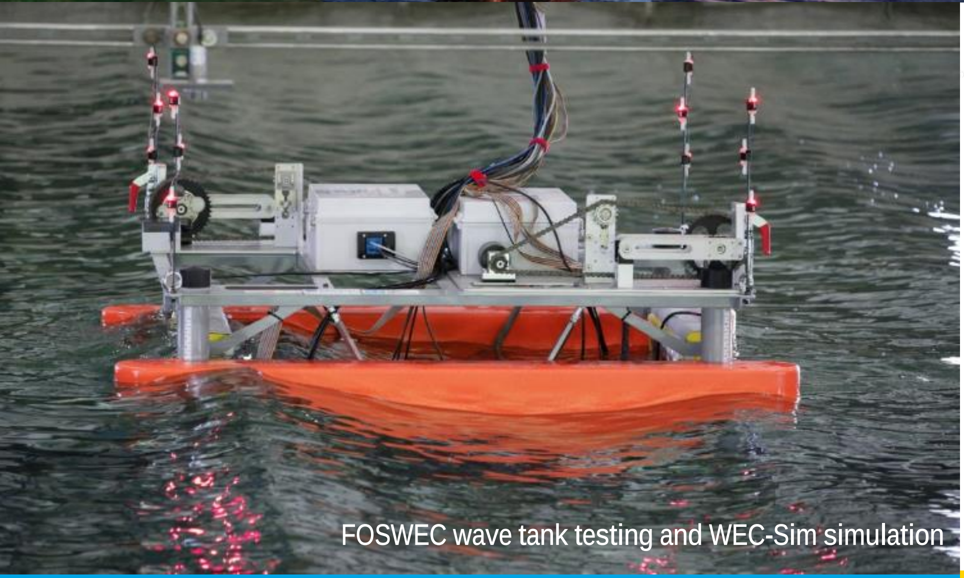
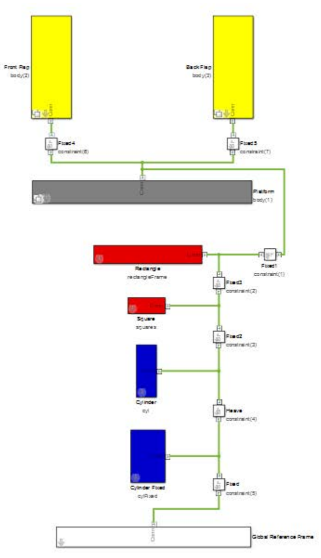
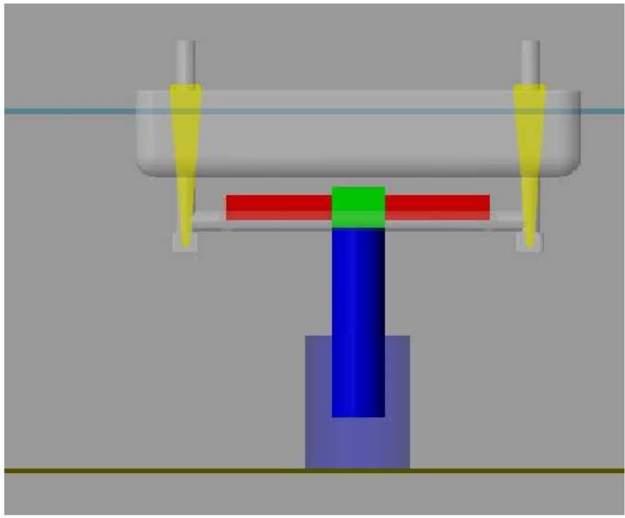
Energy Efficiency & Renewable Energy







FOSWEC wave tank testing and WEC-Sim simulation

WEC-Sim Webinar #2

nlhydro, non-hydro, b2b

May 24, 2017

Yi-Hsiang Yu and Jennifer van Rij (NREL)
Kelley Ruehl (Sandia)

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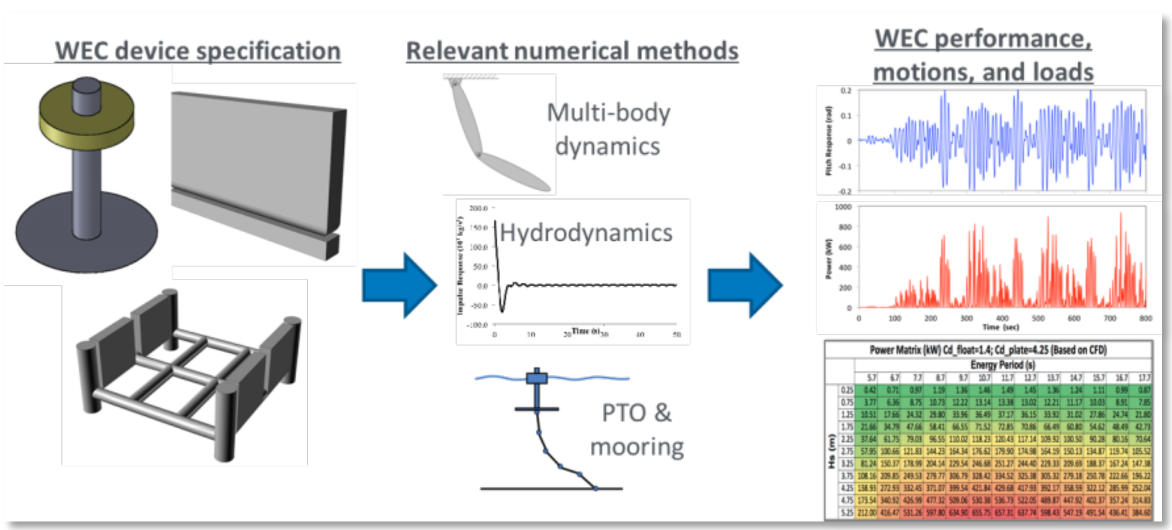
WEC-Sim Team

- Kelley Ruehl (Sandia)
- Yi-Hsiang Yu (NREL)
- Jennifer van Rij (NREL)



Schedule

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Advanced Feature Webinars *1hr each*

- **April 18:** bemio and mcr, application for power matrix
- **May 24:** nl-hydro, b2b, non-hydro ~~and drag~~
- **June 7:** pto and control, application for desalination
- **July 18:** mooring and visualization
- ***Available Online***: http://wec-sim.github.io/WEC-Sim/webinars.html

Training Courses

- **May 1:** *1hr* WEC-Sim workshop at METS, for new users
- **TBD:** *half-day* WEC-Sim code structure course, for advanced users/developers

WEC-Sim Webinar #2

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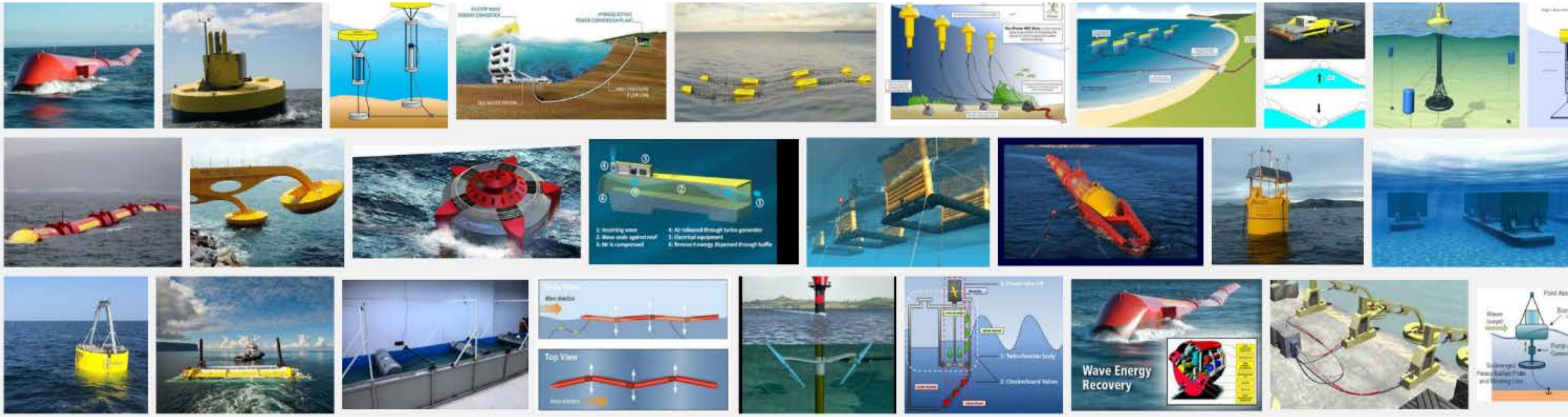


simu.nlhydro

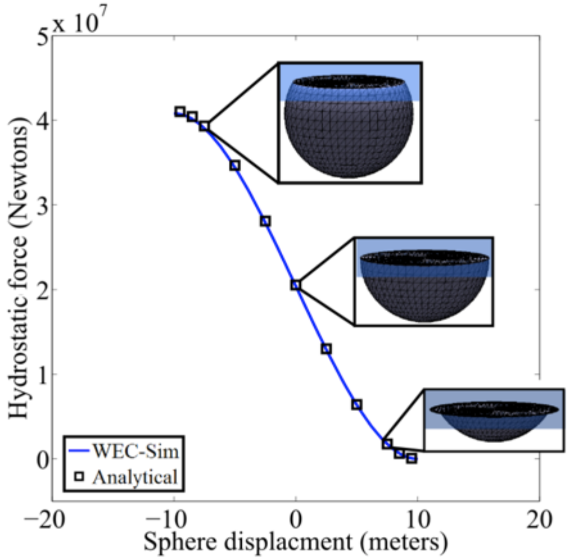
Non-linear hydro –statics and -dynamics

Yi-Hsiang (NREL)

Non-Linear Hydrodynamics

WEC-Sim has the option to include the two non-Linear hydrodynamic forcing terms when solving the system dynamics of WECs:

- Nonlinear hydrostatic restoring forces
- Nonlinear Froude-Krylov forces



A weakly nonlinear approach is applied to account for the nonlinear hydrodynamic forces induced by the instantaneous water surface elevation, body position and geometry of the floating body.

Non-Linear Hydrodynamics

- Because linear wave theory is used to determine the flow velocity and pressure field, the values become unrealistically large for wetted panel that are above the mean water level.

- To correct this, the Wheeler stretching method is used, which forces the water column (based on the instantaneous wave elevation) to have a height that equals to the water depth when calculating the flow velocity a

$$z^* = \frac{D(D+z)}{(D+\eta)} - D$$

- The method is not intended to model highly nonlinear hydrodynamic events, such as wave slamming and wave breaking.

Non-Linear Settings

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The nonlinear hydrodynamics option can be used by setting simu.nlHydro = 2 or simu.nlHydro = 1 in your WEC-Sim input file.

wecSimInputFile.m

```
% DOF=5;  % comment out since will do all of them.

%% Simulation Data
simu = simulationClass();                       %Create the Simulation Variable
simu.endTime=100;                                   % Simulation End Time [s]
simu.dt = 0.05;                                     % Simulation Delta_Time [s]
simu.simMechanicsFile = 'ellipsoid.slx';                 % Specify Simulink Model
%simu.mode='rapid-accelerator';                     % Specify Simulation Mode
simu.rho=1025;
simu.mode='normal';
simu.explorer='off';                                % Turn SimMechanics Explorer
simu.CITime           = 30;
simu.rampT            = 50;
simu.nlHydro          = 2;
simu.dtFeNonlin=2*simu.dt;
%simu.dtCITime          = 0.1;
```

- Typically, simu.nlHydro = 2 is recommended if nonlinear hydrodynamic effects need to be used.
- Note that simu.nlHydro = 1 only considers the nonlinear restoring and Froude-Krylov forces based on the body position and mean wave elevation.

Non-Linear Settings

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An option is available to reduce the nonlinear simulation time is to specify a nonlinear time step:

- simu.dtFeNonlin=N*simu.dt, where N is number of increment steps.

wecSimInputFile.m

```
% DOF=5;  % comment out since will do all of them.

%% Simulation Data
simu = simulationClass();                   %Create the Simulation Variable
simu.endTime=100;                               % Simulation End Time [s]
simu.dt = 0.05;                                  % Simulation Delta_Time [s]
simu.simMechanicsFile = 'ellipsoid.slx';             % Specify Simulink Model
%simu.mode='rapid-accelerator';                   % Specify Simulation Mode
simu.rho=1025;
simu.mode='normal';
simu.explorer='off';                             % Turn SimMechanics Explorer
simu.CITime         = 30;
simu.rampT          = 50;
simu.nlHydro        = 2;
simu.dtFeNonlin=2*simu.dt;
%simu.dtCITime        = 0.1;
```

- As the ratio of the nonlinear to system time step increases, the computation time is reduced, but again, at the expense of the simulation accuracy.

Non-Linear Settings

- WEC-Sim’s nonlinear hydrodynamic option may be used for regular or irregular waves, but not with user-defined irregular waves.

- To use nonlinear hydrodynamic option for user user-defined irregular waves, the user has to use FFT to compute the spectrum and the corresponding phases for the waves.

STL File Generation

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- When the nonlinear option is turned on, the geometry file (*.stl) (previously only used for visualization purposes in linear simulations) is used as the discretized body surface on which the non-linear pressure forces are integrated.

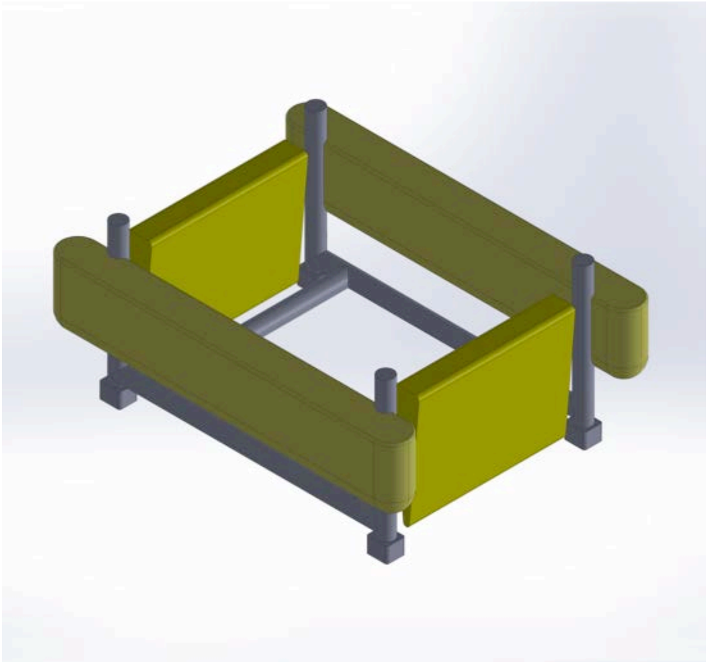
- STL (STereoLithography) is a file format native to the stereolithography CAD software created by 3D Systems.

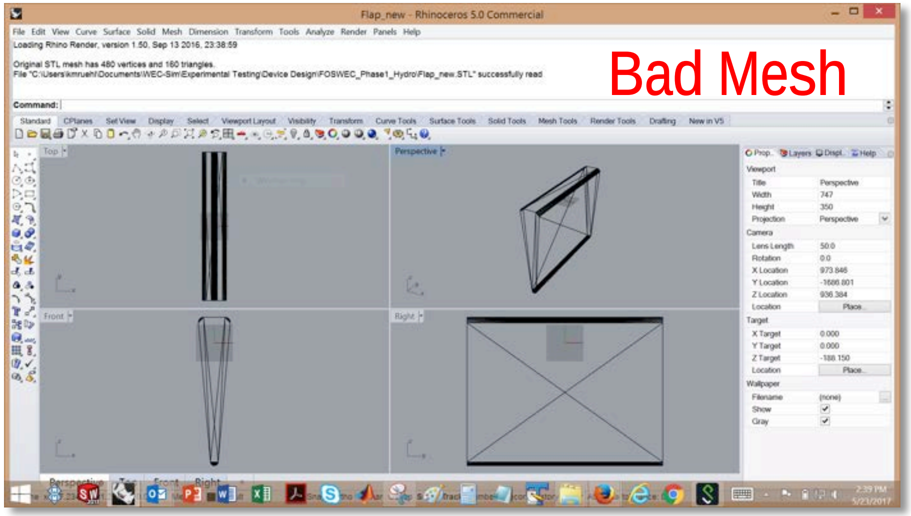
- It is widely used for rapid prototyping, 3D printing and computer-aided manufacturing.

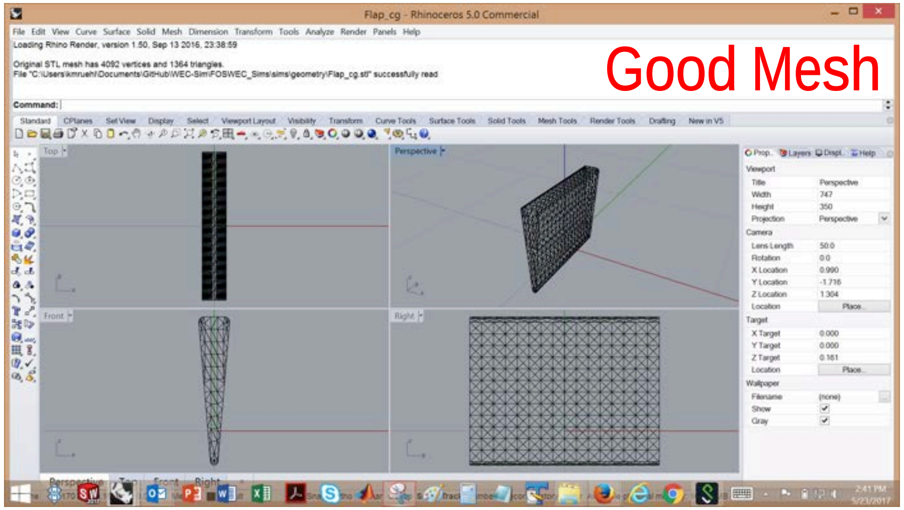
- The STL format specifies both ASCII and binary representations. WEC-Sim only accepts the ASCII format.

STL File Generation

- A good STL mesh resolution is required.

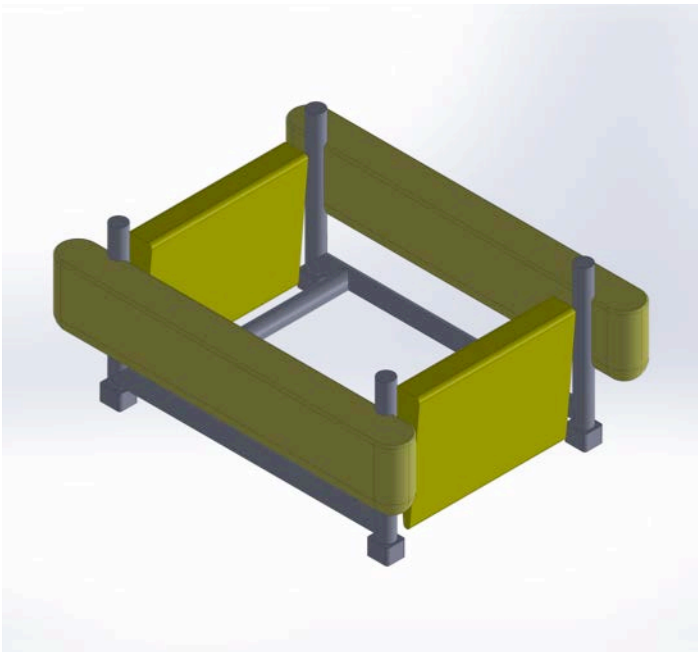


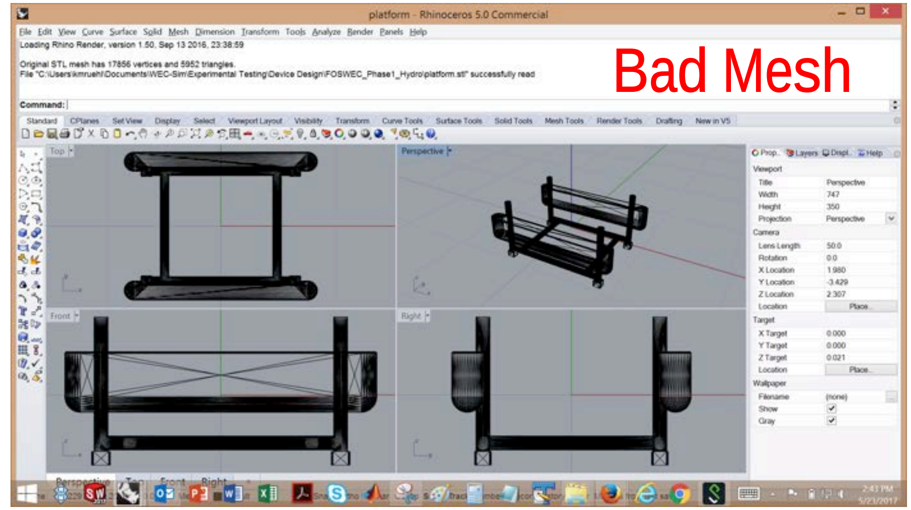


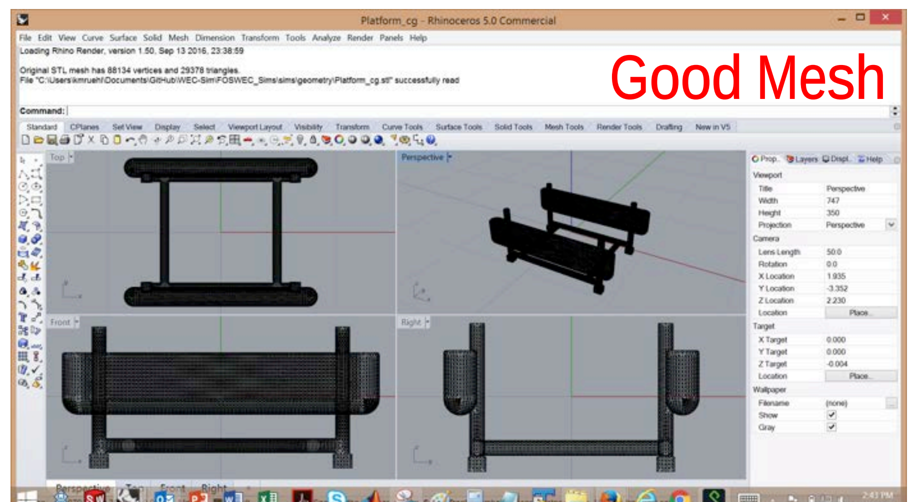


STL File Generation

- A good STL mesh resolution is required.







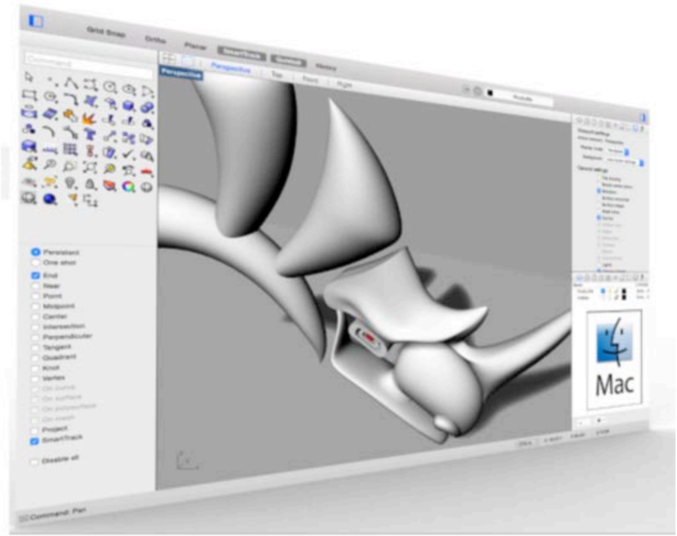
STL File Generation

- The simulation accuracy will increase with increased surface resolution (i.e. the number of discretized surface panels specified in the .stl file), but the computation time will also increase.

- There are many ways to generate an STL file, however it is important to verify the quality of the mesh before running WEC-Sim simulations with the non-linear hydro flag turned on.

STL File Generation

- An STL file can be exported from from most CAD programs, but few allow adequate mesh refinement.
- A good program to perform STL mesh refinement is Rhino.



https://www.rhino3d.com/

- Some helpful resources explaining how to generate and refine an STL mesh in Rhino3d are:
  - https://wiki.mcneel.com/rhino/meshfaqdetails
  - https://vimeo.com/80925936

Tutorial - Heaving Ellipsoid

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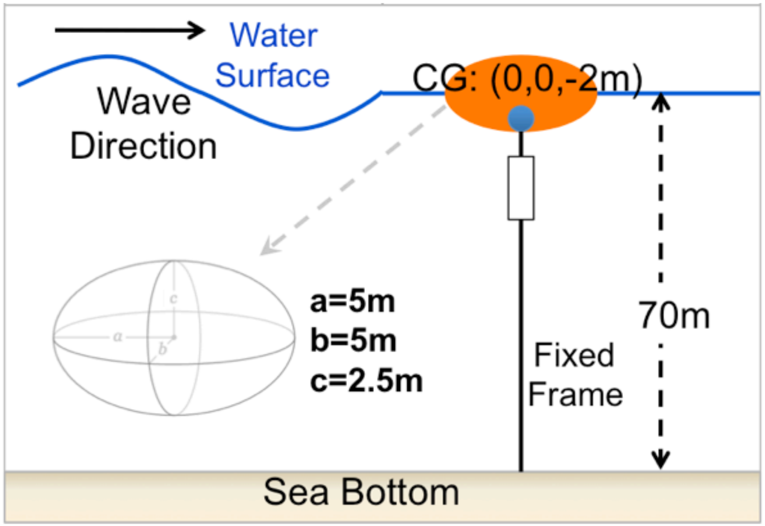
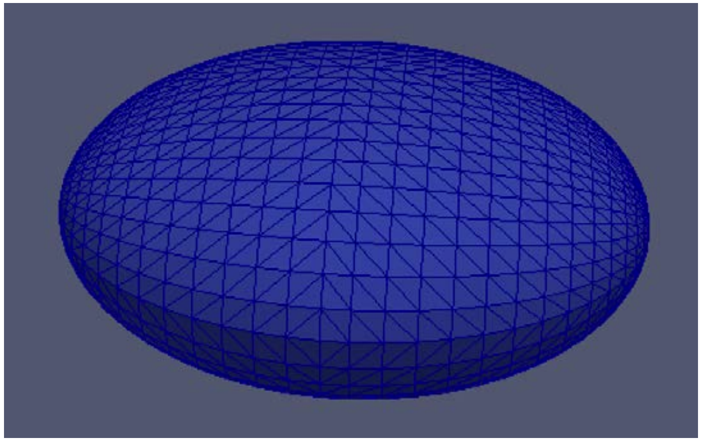
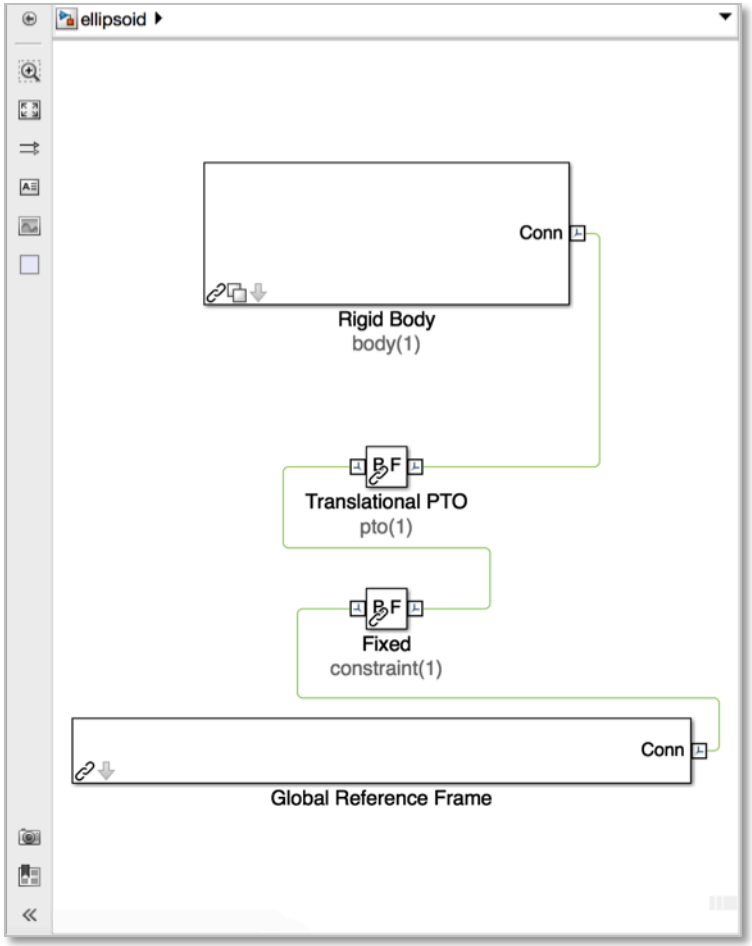
- An example is provided in the WEC-Sim Application repository
  https://github.com/WEC-Sim/WEC-Sim_Applications





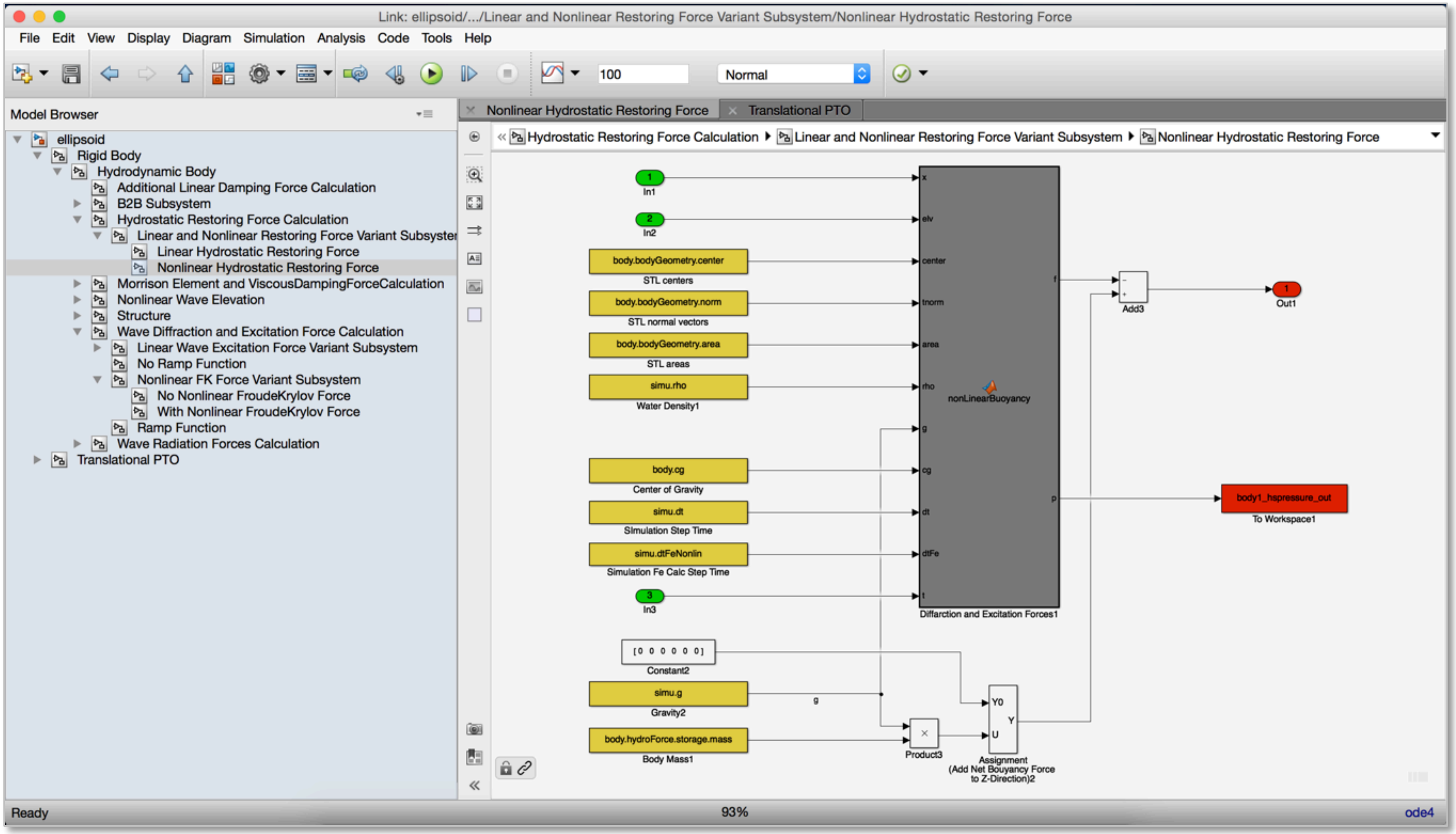


Tutorial - Heaving Ellipsoid

```
%% Simulation Data
simu = simulationClass();                    %Create the Simulation Variable
simu.endTime=100;                                % Simulation End Time [s]
simu.dt = 0.05;                                   % Simulation Delta_Time [s]
simu.simMechanicsFile = 'ellipsoid.slx';              % Specify Simulink Model File
simu.rho=1025;
simu.mode='normal';
simu.explorer='off';                              % Turn SimMechanics Explorer
simu.CITime         = 30;
simu.rampT          = 50;
simu.nlHydro        = 2;
simu.dtFeNonlin=2*simu.dt;

% Wave Information
waves = waveClass('regular');                  %Create the Wave Variable and Specify Type
waves.H = 4;                                  % Wave Height [m]
waves.T = 6;                                  % Wave period [s]

%Body Data
body(1) = bodyClass('wamit/ellipsoid.h5');% Initialize bodyClass for Float
body(1).mass = 'equilibrium';                    % Mass from WAMIT [kg]
body(1).momOfInertia = ...                       % Moment of Inertia [kg-m^2]
    [1.375264e6 1.375264e6 1.341721e6];
body(1).geometryFile = 'geometry/elipsoid.stl' ;
body(1).viscDrag.cd=[1 0 1 0 1 0];
body(1).viscDrag.characteristicArea=[25 0 pi*5^2 0 pi*5^5 0];

% PTO and Constraint Parameters
constraint(1) = constraintClass('Constraint1');
constraint(1).loc = [0 0 -12.5];                         %Constraint Location [m]

pto(1) = ptoClass('PTO1');                  % Initialize ptoClass for PTO1
pto(1).k=0;                                 % PTO Stiffness Coeff [N/m]
pto(1).c=1200000;                                 % PTO Damping Coeff [Ns/m]
pto(1).loc = [0 0 -12.5];
```

Code Structure

- Nonlinear hydrostatic restoring forces



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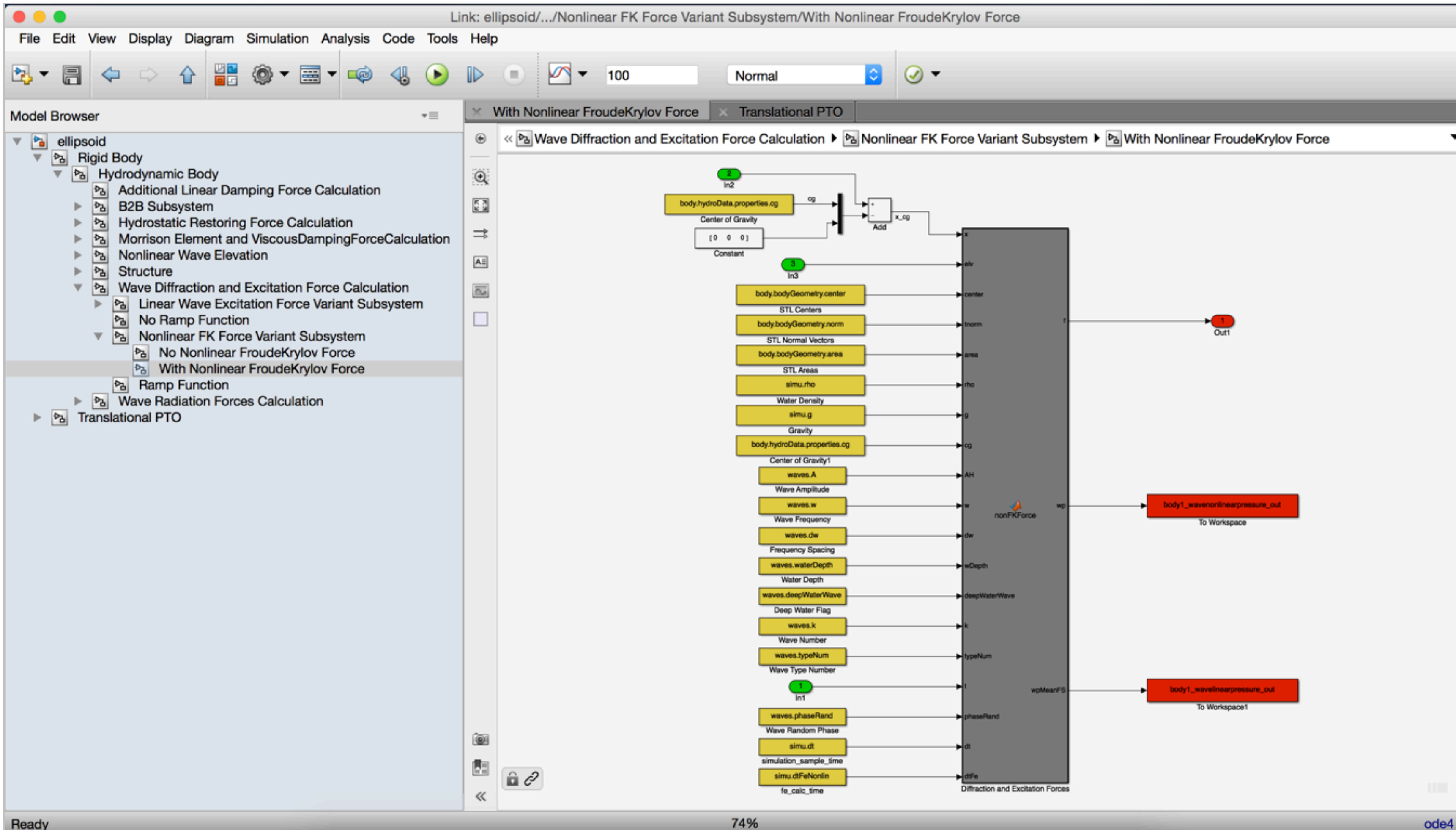
- Nonlinear Froude-Krylov forces



WEC-Sim Updates and Notes

- To reduce the output file size for the nonlinear hydro runs, the pressure distribution from nonlinear hydrodynamics calculation is NOT save in the mat file as default (latest commits on May 23, 2017).

- For multiple condition runs, it is recommended to save the SELECTED data from each simulation in different name using the "userDefinedFunctionsMCR.m" file

- If the body geometry is symmetric along the incoming wave direction, it is recommended to use 3DOF (instead of 6DOF) to reduce potential numerical instability, particularly when nonlinear hydrodynamics option is used.

Possible Future Improvements

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- Computational efficiency
- Nonlinear waves
- Documentation

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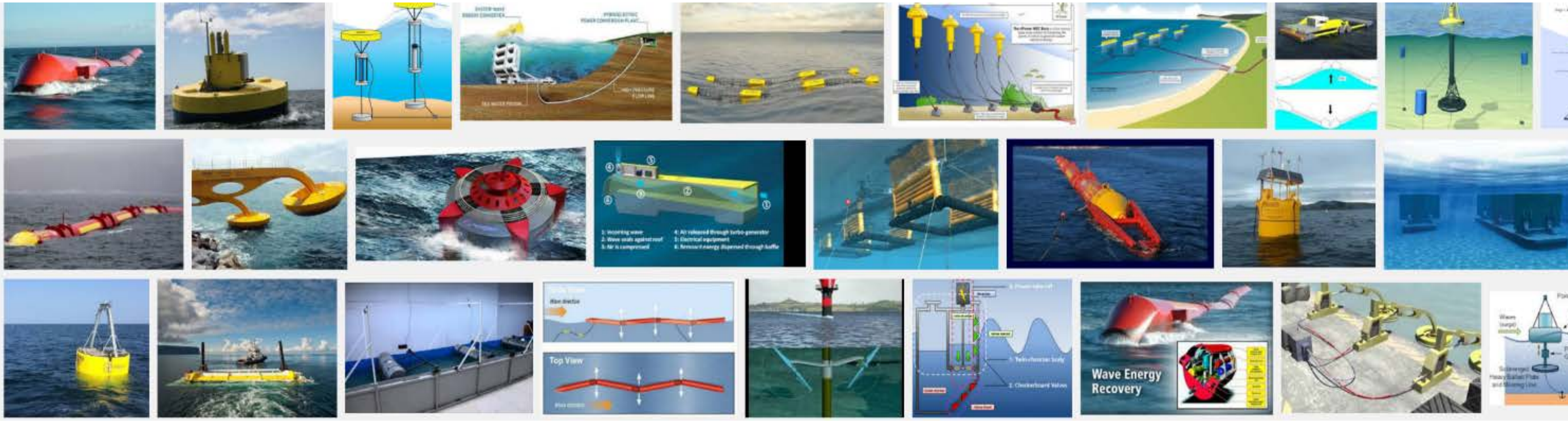


Non-hydrodynamic Bodies

body(i).nhBody

Kelley Ruehl (Sandia)

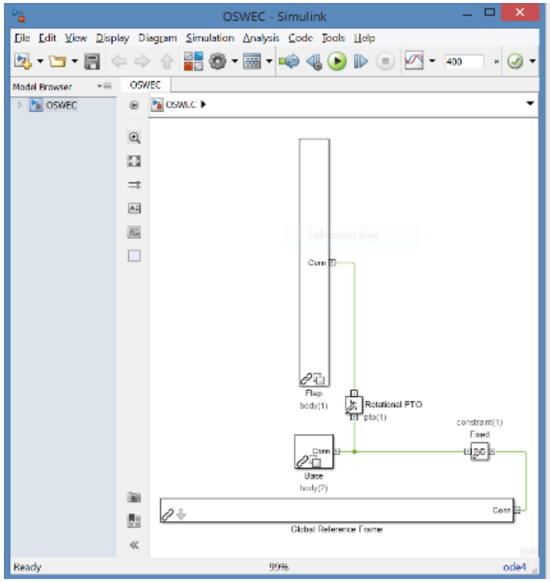
Non-Hydro Bodies

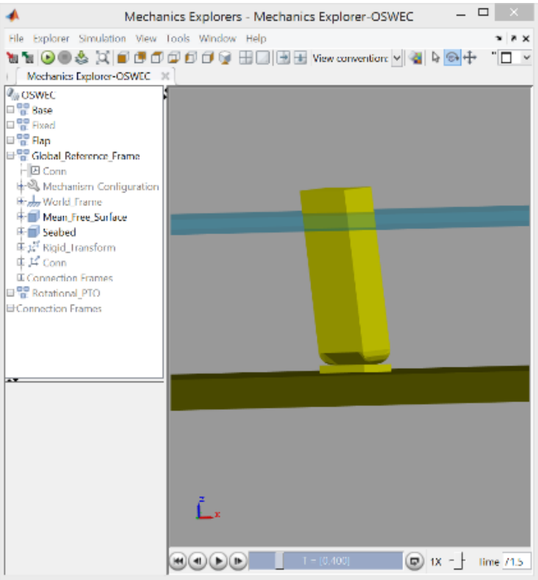
OSWEC Tutorial

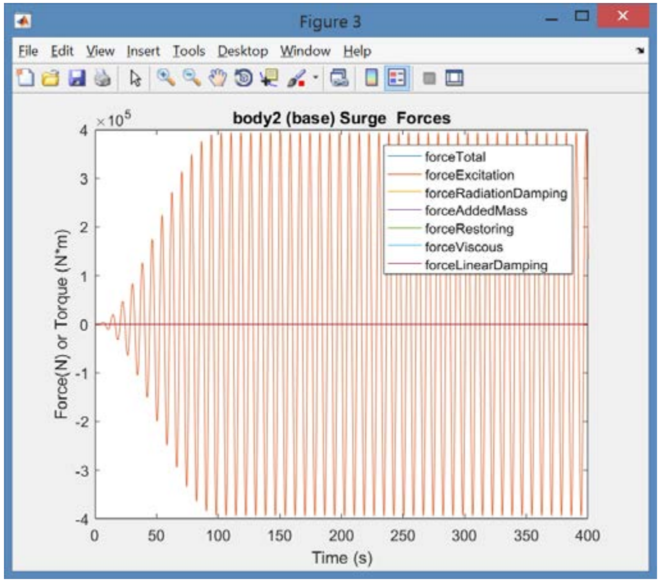
https://github.com/WEC-Sim/WEC-Sim/tree/master/tutorials/OSWEC

- Models base, *body(2)*, as a fixed hydrodynamic body
- Determines hydro forces on base, ie: wave excitation force
- No radiation or restoring since body is fixed

```
%% Base
body(2) = bodyClass('hydroData/oswec.h5');   % Initialize bodyClass for Base
body(2).geometryFile = 'geometry/base.stl';    % Geometry File
body(2).mass = 'fixed';                        % Creates Fixed Body
```







Non-Hydro Bodies

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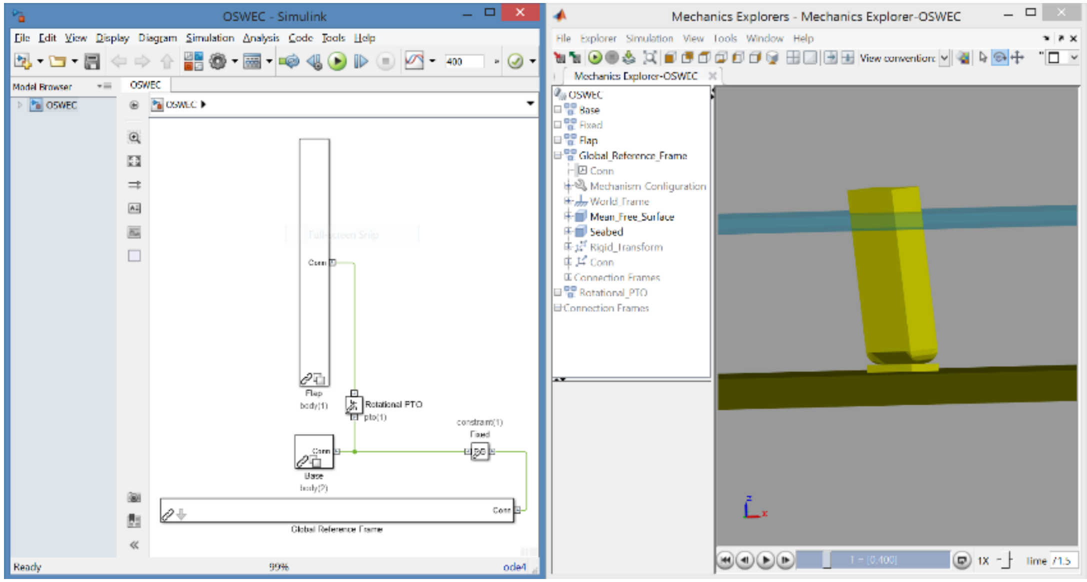
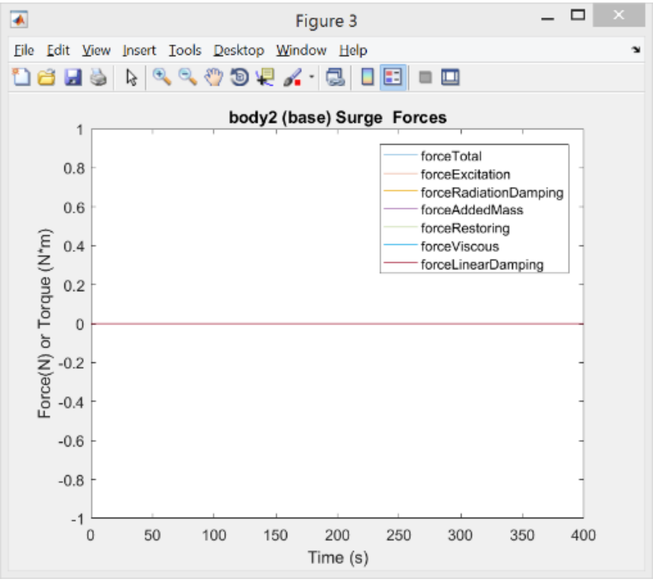
OSWEC_nhBody Application

https://github.com/WEC-Sim/WEC-Sim_Applications/tree/master/OSWEC_nhBody

- Models base, *body(2)*, as a fixed non-hydrodynamic body
- No hydro forces on base, ie: excitation, radiation, restoring
- Simplifies model and reduces required BEM solutions
- NOTE: non-hydro bodies do *not* have to be fixed





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OSWEC_nhBody Application: Input File

https://github.com/WEC-Sim/WEC-Sim_Applications/tree/master/OSWEC_nhBody

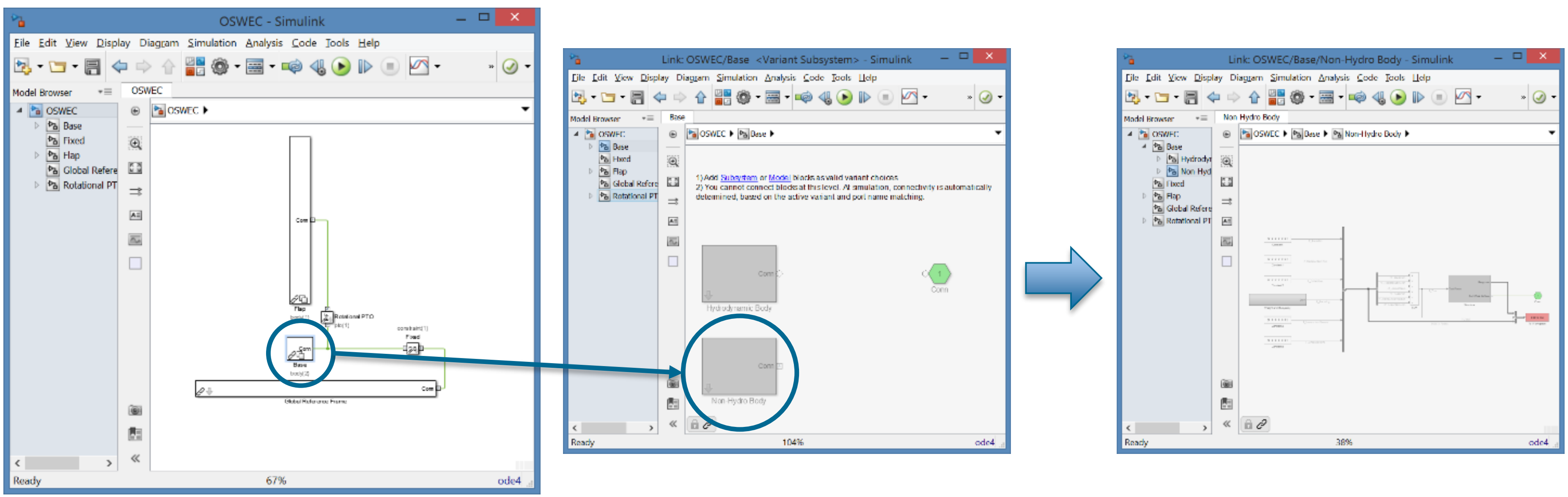
- Initialize body class (without *.h5) and name body
- Set *body(2).nhBody = 1;*
- Define mass, moments, cg, and displaced volume
- Define *.STL for visualization

```
%% Base
% body(2) = bodyClass('hydroData/oswec.h5');    % Initialize bodyClass for Base
    body(2) = bodyClass('');
    body(2).nhBody = 1;
    body(2).name = 'base';
body(2).geometryFile = 'geometry/base.stl';     % Geometry File
% body(2).mass = 'fixed';
    body(2).mass = 999;
    body(2).momOfInertia = [1 1 1];
    body(2).cg = [0 0 0];
    body(2).dispVol = 0;
```

OSWEC_nhBody Application: Simulink Model

https://github.com/WEC-Sim/WEC-Sim_Applications/tree/master/OSWEC_nhBody

- *body(2).nhBody = 1;*
- Turns on *Non-Hydro Body* variant subsystem
- Only applies gravity and buoyancy forces to base



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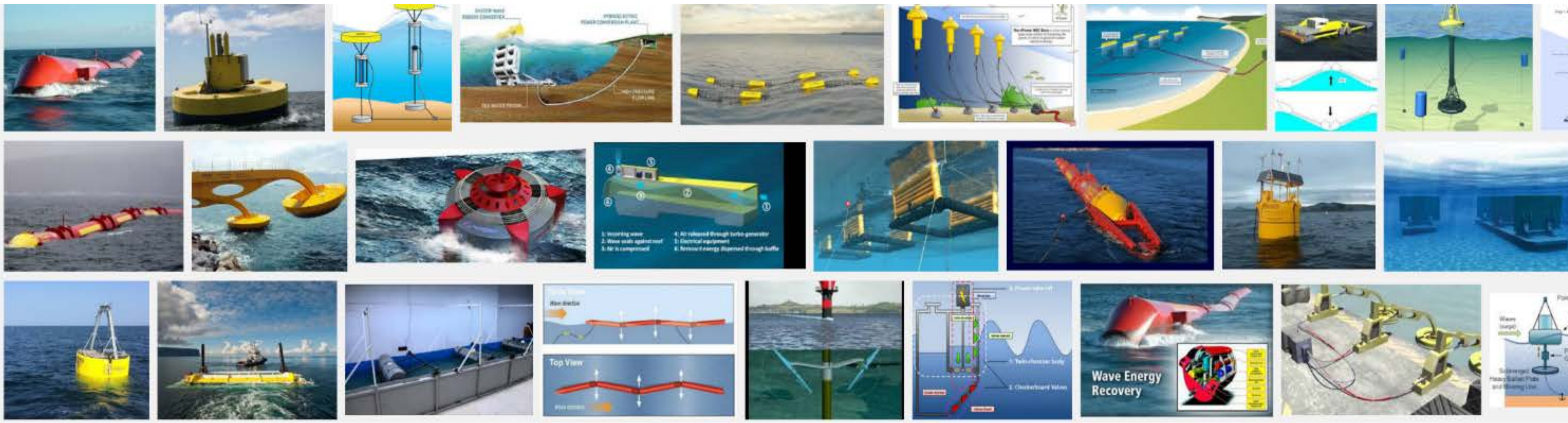


Body-to-Body Interactions

simu.b2b

Kelley Ruehl (Sandia)

WEC-Sim Theory

- Uses the radiation and diffraction method and calculates the hydrodynamic forces from frequency-domain Boundary Element Method (BEM)
- Dynamics simulated by solving time-domain equation of motion (Cummins, 1962)

$$m\ddot{X}(t) = F_B(t) + F_{ext}(t) + F_{rad}(t) + F_v(t) + F_{PTO}(t) + F_m(t)$$

- $F_B(t)$: Hydrostatic Restoring force
- $F_{ext}(t)$: Wave excitation & diffraction force (BEM)
- $F_{rad}(t)$: Radiation force: added mass and radiation damping (BEM)
- $F_v(t)$: Viscous force
- $F_{PTO}(t)$: Power take-off force
- $F_m(t)$: Mooring force

$$F_{ext}(t) = \Re\left[R_f \int_0^{\infty} F_x(\omega_r)\, e^{i(\omega_r t+\phi)} \sqrt{2S(\omega_r)d\omega_r}\right]$$

BEM ($F_x(\omega_r)$)

$$= \int_{-\infty}^{\infty} \eta(\tau)\, f_e(t-\tau)d\tau$$

BEM (f_e)

$$F_{rad}(t) = -A_{\infty}\ddot{X} - \int_0^t K(t-\tau)\dot{X}(\tau)d\tau$$

BEM ($-A_{\infty}$), BEM (K)

B2B Interactions

- Buoy Forces

$$F_{e_1}(t) - F_{r_{11}}(t) - F_{r_{12}}(t) = K_{hs}x_1 + b_{v_1}\dot{x}_1 + (m_1 + A_{11}(\infty))\ddot{x}_1$$

- Spar/Plate Forces

$$F_{e_2}(t) - F_{r_{22}}(t) - F_{r_{21}}(t) - F_m(x_2,\dot{x}_2) = b_{v_2}\dot{x}_2 + (m_2 + A_{22}(\infty))\ddot{x}_2$$

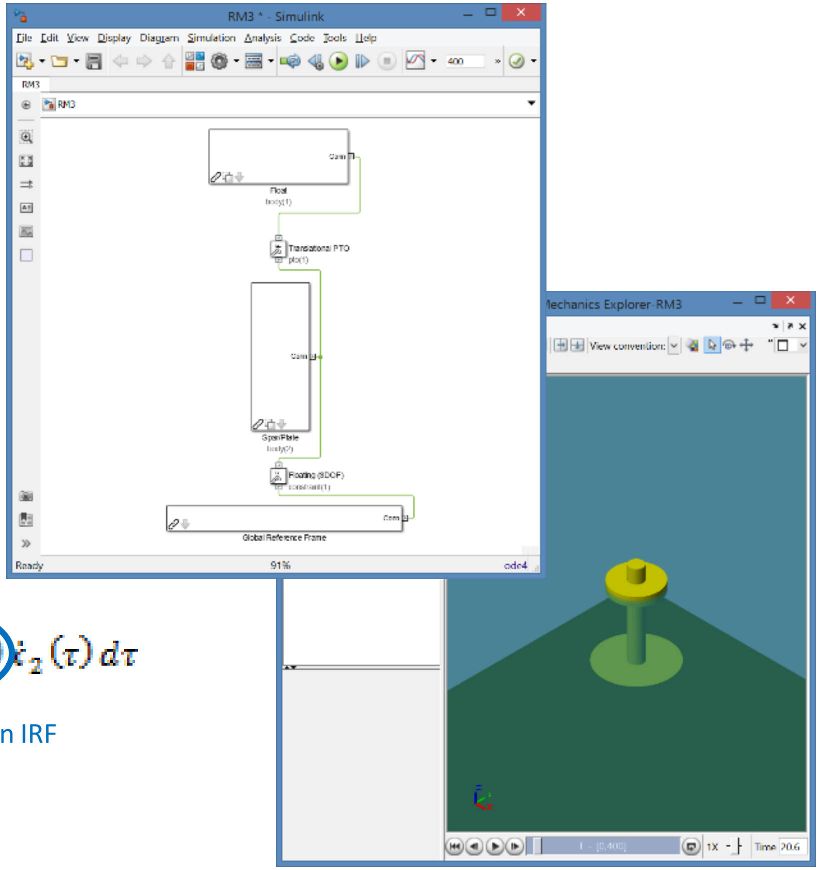
- Radiate force created by each body's motion

$$F_{r_{11}} = \int_{-\infty}^{t} k_{r_{11}}(t-\tau)\dot{x}_1(\tau)\,d\tau$$

Buoy Radiation IRF

$$F_{r_{22}} = \int_{-\infty}^{t} k_{r_{22}}(t-\tau)\dot{x}_2(\tau)\,d\tau$$

Plate Radiation IRF



- Coupled Radiation Forces:

$$F_{r_{12}} = \int_{-\infty}^{t} k_{r_{12}}(t-\tau)\dot{x}_2(\tau)\,d\tau + A_{12}(\infty)\ddot{x}_2$$

Coupled Radiation IRF

$k_{12} = k_{21}$

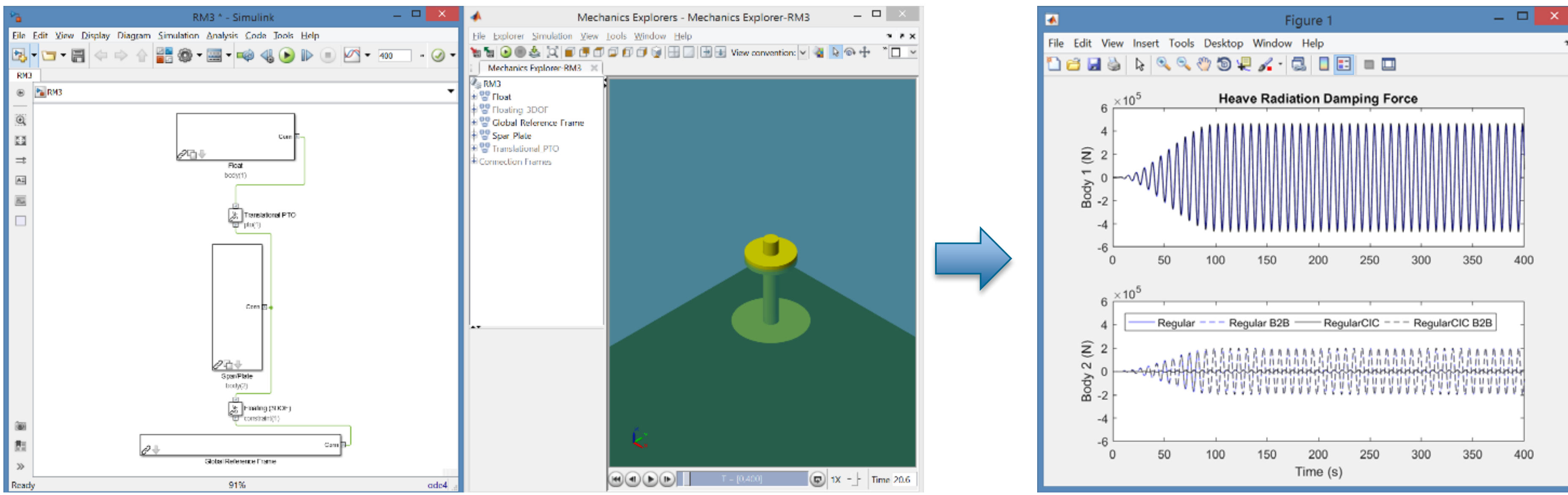
$$F_{r_{21}} = \int_{-\infty}^{t} k_{r_{21}}(t-\tau)\dot{x}_1(\tau)\,d\tau + A_{21}(\infty)\ddot{x}_1$$

B2B Interactions

RM3_B2B Application

https://github.com/WEC-Sim/WEC-Sim_Applications/tree/master/RM3_B2B

- Models RM3 with B2B on/off
- Compares different B2B implementations
  - *Regular*
  - *RegularCIC*



RM3_B2B Application: Input File

https://github.com/WEC-Sim/WEC-Sim_Applications/tree/master/RM3_B2B

- Initialize simulation class as usual
- Set *simu.b2b = 1;*

```
%% Simulation Data
simu = simulationClass();                   %Create the Simulation Variable
simu.simMechanicsFile = 'RM3.slx';          %Location of Simulink Model File
% simu.mode = 'normal';                     %Specify Simulation Mode ('normal','ac
% simu.explorer='on';                       %Turn SimMechanics Explorer (on/off)
% simu.startTime = 0;                       %Simulation Start Time [s]
simu.endTime=400;                           %Simulation End bdcloseTime [s]
simu.solver = 'ode4';                       %simu.solver = 'ode4' for fixed step &
simu.dt = 0.1;                              %Simulation time-step [s]
simu.rampT = 100;                           %Wave Ramp Time Length [s]
simu.b2b = 1;
```

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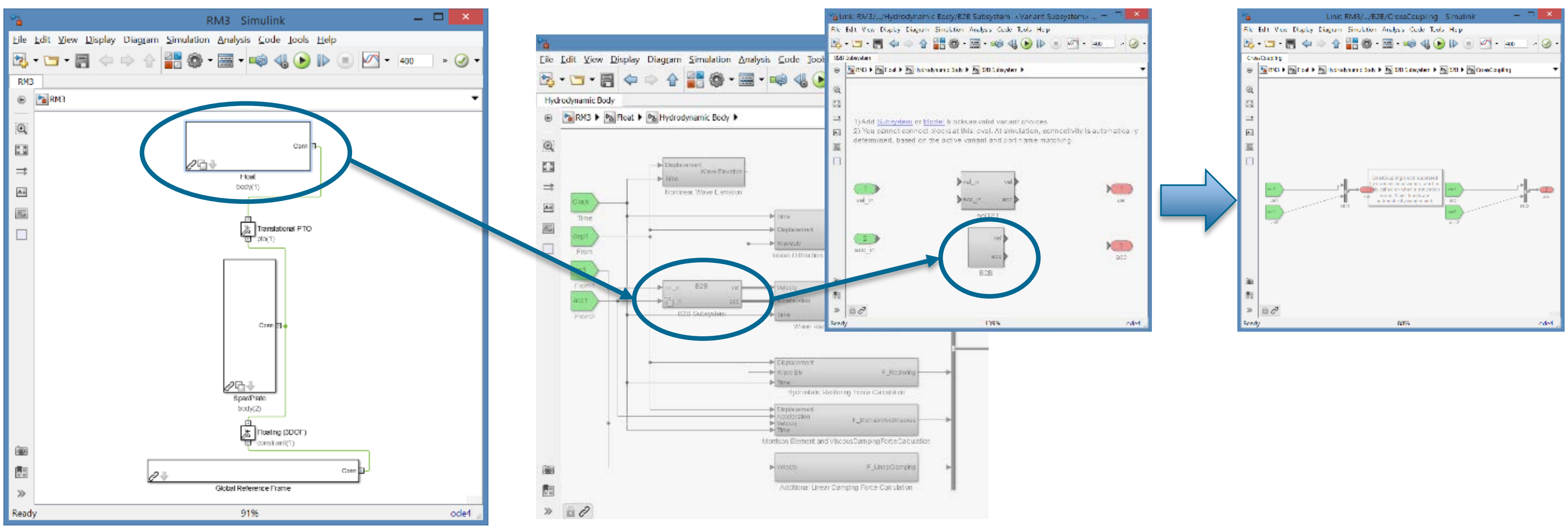
RM3_B2B Application: Simulink Model

https://github.com/WEC-Sim/WEC-Sim_Applications/tree/master/RM3_B2B

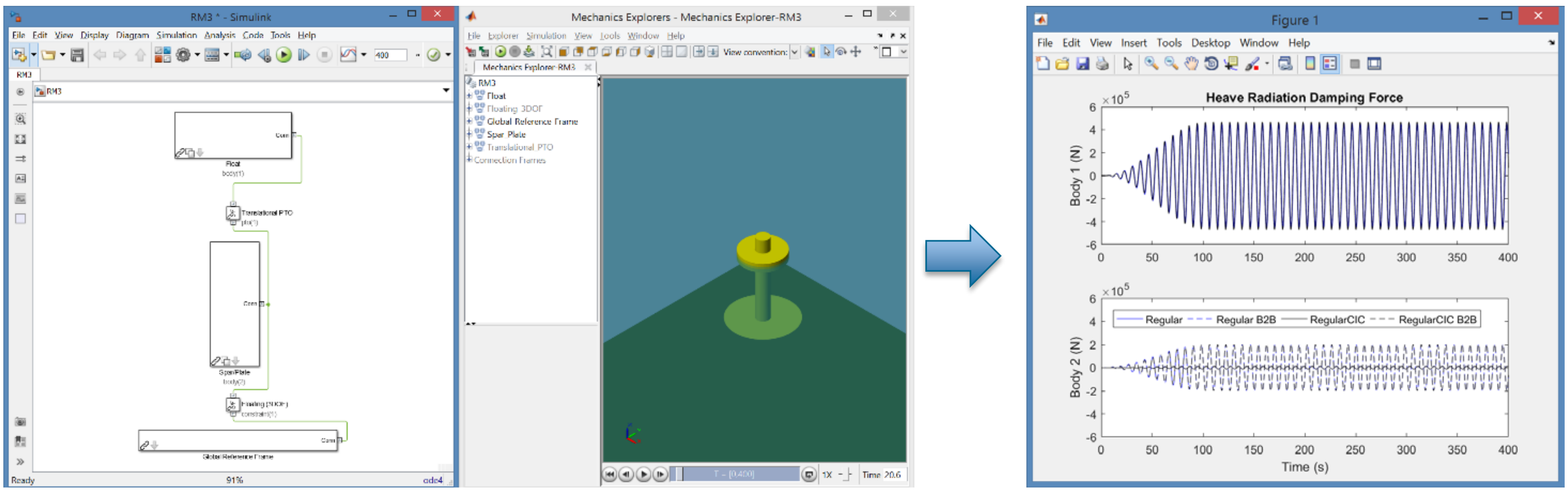
- *simu.B2B = 1;*
- Turns on *B2B* variant subsystem
- Merges each body's velocity and acceleration signals into one velocity and acceleration vector, ex: for 2 bodies [6x1] → [12x1]



RM3_B2B Application

https://github.com/WEC-Sim/WEC-Sim_Applications/tree/master/RM3_B2B

- Implementation depends on numerical method
  - *Regular* uses coupled radiation coefficients for each body based on incident wave period
  - *RegularCIC* uses Impulse Response Function (IRF) formulation of coupled wave radiation



Thank you!

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Upcoming scheduled webinars and training courses…

Advanced Feature Webinars *1hr each*

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- **May 24:** nl-hydro, b2b, non-hydro and drag
- **June 7:** PTO and control, application for desalination
- **July 18:** Mooring and visualization
- ***Available Online***: http://wec-sim.github.io/WEC-Sim/webinars.html

Training Courses

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