COLUMBIA POWER TECHNOLOGIES

power from the next wave

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Version	Date	Summary
1.0	6/30/2017	Original release
2.0	12/20/17	Major revision… loads now provided as time series
2.1	3/19/18	Update for 9 bodies… additional description of load calculations and load / inertia balance

1 INTRODUCTION

The purpose of this document is to describe the loads provided by CPwr to Glosten for the purpose of designing the prototype StingRay WEC (see "DE-EE0006610 SR-EDR-0100" for more details). Previously provided documents describing loads should be discarded. The loads are now being provided as time series (not discrete minima and maxima cases), and the joint loads as reported by AQWA are provided (rather than CPwr assumptions to translate these loads to other locations).

2 MODEL OVERVIEW

Loads are assessed computationally using fully coupled time-domain numerical simulations, accounting for all load contributions simultaneously (ANSYS AQWA Naut). Morison bodies are used (as opposed to a Boundary Element Method panel model bodies).

WEC is modeled as 9 substructures. Bodies are connected primarily by 0 DOF rigid joints, leading to a 'central body assembly' composed of 8 substructures, and a 'float body assembly' substructure. Float arms are connected to the nacelle via a 1 DOF rotating joint (about the PTO axis of rotation). Schematics labeling substructures and joints are provided as Figure 1 and Figure 2.

PTO model applies torque to the nacelle, and to the float arms. PTO torque includes mechanical friction elements as well as generator torque.

The mooring system is modeled with multiple elements to follow the installed mooring at the planned deployment site. The umbilical cable is included in the mooring model. The AQWA mooring model is depicted in Figure 3. Loads are reported at four interfaces: two fore bridle lines, one aft tether line, and the umbilical.

The models were simulated with a time step of 0.02 s (0.01 s for extreme seas), and the first minute is discarded as the WEC motion is ramping up. All signals were down sampled to 10 Hz for delivery to Glosten.

Imaginary 'end stops' are added to the model, which apply force to the float if it is about to rotate over the top or the bottom of the nacelle. The model somewhat overestimates the float motion (e.g. sending it over the top in conditions where this is not expected, per scaled tank testing on a similar WEC), and so these 'end stops' are used to keep the float nominally in the expected position. Windows of time around these 'end stop' force applications are flagged as such, and are to be excluded from analysis.

WEC response is modeled in 24 operational sea states and 2 extreme sea states. PM spectrum is utilized, and directional spreading is defined using a cos-N formulation (cosine raised to a specified power). A depth of 80 m is modeled. Directional wave fields are realized by simulating multiple unidirectional spectra, each with its own direction.

WEC generator is damped in operational sea states, and both damped and freewheeling cases are modeled in the extreme sea state. No wind or current loads are included in the models. Design Load Cases (DLCs) are specified in CPwr document "Design Load Cases for Structural Optimization". Additional, optional DLCs are also listed in "Design Load Cases for Structural Optimization".

Location of all centers of gravity (C.G.s) of each substructure, as well as mass and moments of inertia, are provided in an accompanying spreadsheet "design inputs for Glosten 16mar2018". C.G.s are given with respect to the global origin, with the WEC in its definition position. Masses provided are those assumed in the loads modeling effort.

The definition position is shown in the SolidWorks model "L6092.SLDASM".

The WEC model in SolidWorks is at a conceptual level; the model in AQWA is simplified further (see Fig 1 for comparison of side views in definition position). All substructures have equivalent volumes. Note that Figure 1 and Figure 2 were not updated to reflect consolidation of float and arms to a single body. The 'design inputs' spreadsheet provided correctly identifies bodies and joints.

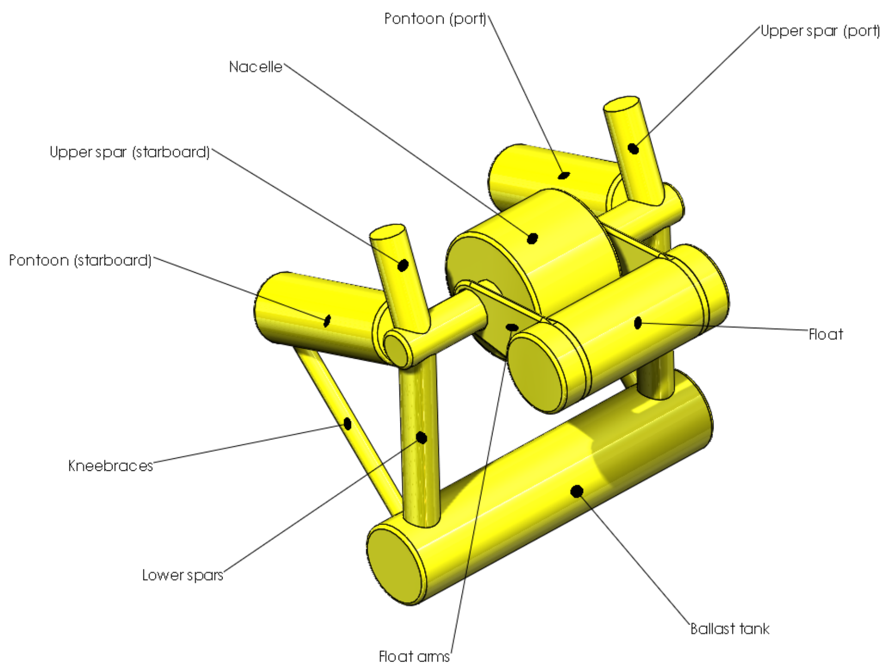

Figure 1 – Schematic of StingRAY WEC with substructures labeled.

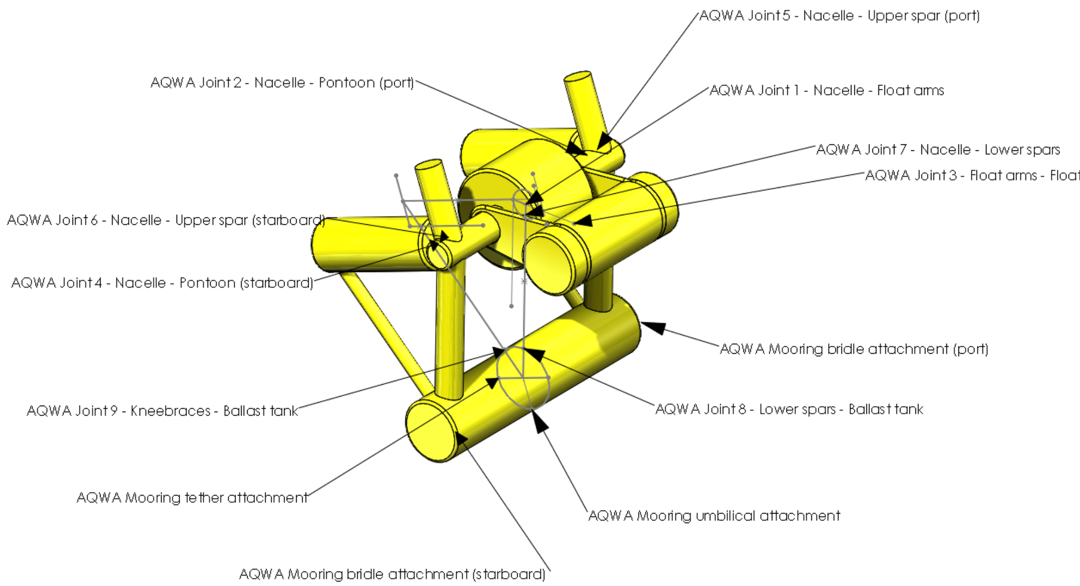

Figure 2 – Schematic of StingRAY WEC with joints labeled.

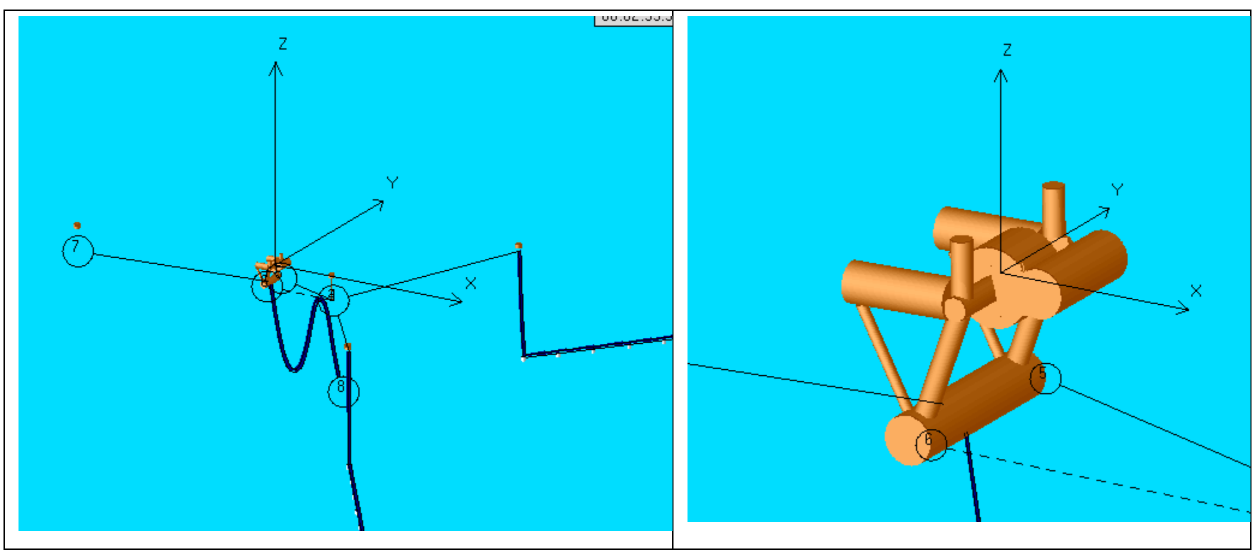

Figure 3 – Screenshots of AQWA mooring model.

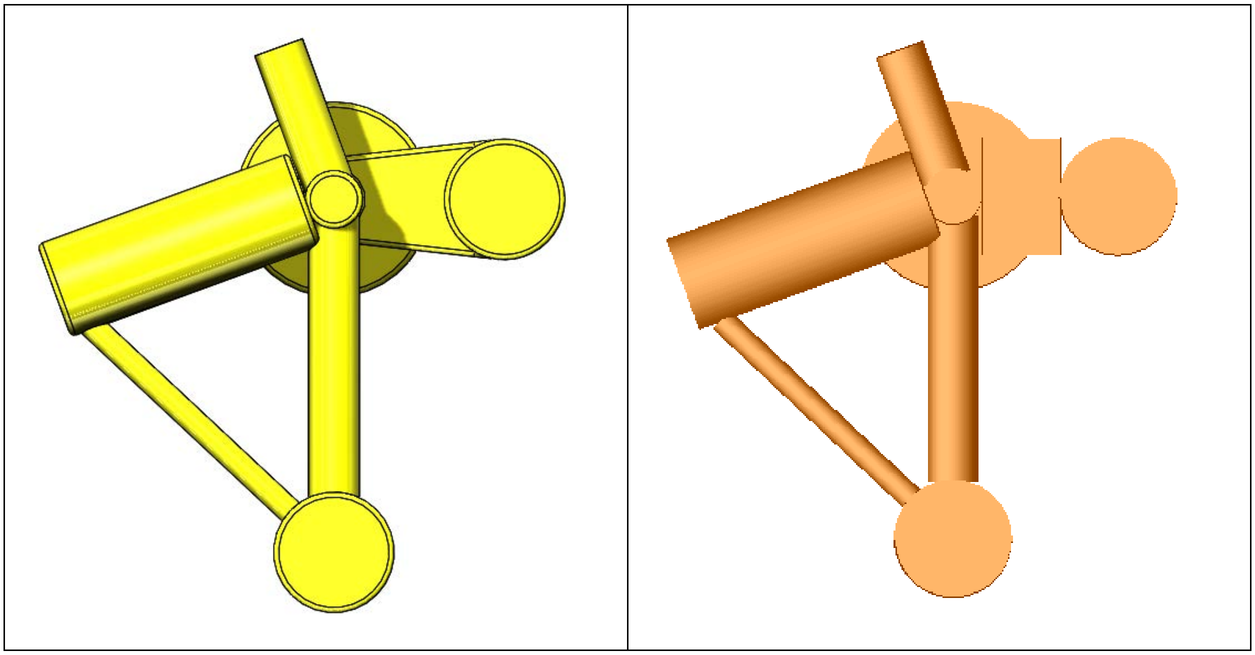

Figure 4 – Schematics showing differences between SolidWorks and AQWA models.

AQWA interfaces (or joints) are specified as at a single point in space, and are shared between two substructures. Neither substructure is required to physically exist at the interface location, as there is conceptually a massless, rigid connection between each substructure and this location.

AQWA does not allow over constrained systems, as the dynamic equations assume rigid bodies. Because of this, for example, the two lower spars (port and starboard) are defined as a single substructure… allowing the nacelle to be connected to the spars which are connected to the ballast tank. If the spars were separate substructures (each attached to the nacelle and to the ballast tank), then there would need to be a 'force loop', and the system would be over constrained.

Note that, due to the nature of the joints in AQWA, the reported loads at the joints are not generally accurate for a real structure. For example, the knee braces are connected at the ballast tank end, but not at the pontoons; as such, the reported moment loads at the pontoon to nacelle tube interface are almost certainly over reported.

The spreadsheet of design inputs specifies the location and characteristics of all joints, as well as the mooring attachment points.

3 DESCRIPTION OF LOADS AND OTHER SIGNALS

Loads are provided for 24 operational sea states, and for two extreme sea states (see DLCs, and sheet 'Sea states' on provided 'design inputs' spreadsheet). The WEC is modeled in its power production mode, with the fore float in its fore position, for the operational sea states. For the extreme sea state, the WEC is modeled with the fore float in the aft. In extreme seas the WEC is modeled both in power production, and additionally with the generator free wheeling, or undamped (assuming some fault that renders the generator unable to create torque). These are the 'critical' design load cases described in the "Design Load Cases" document. Minimum time series length for analysis is specified in this document.

Ten 3-hour simulations are provided for both the damped and undamped spread, head on, extreme sea case. One 3-hour simulation is provided for the damped, bidirectional, extreme sea case, as well as one for the undamped case. In all cases the numbering of the files correlates to the seed used (i.e. 'ex_seastate_3hr_damped_4' uses the same seed as 'ex_seastate_3hr_undamped_4'). Note that the first case of the damped extreme seas failed, and so is not provided.

Loads are provided for each substructure, as well as the loads at the joints as defined in the AQWA model. The loads, as well as other variables provided, are described in detail in the "design inputs" spreadsheet. Note that for extreme seas, where the fore float is assumed to have overtopped and be in the aft position, the x-coordinate of the float and float arms assembly must have its sign reversed (sheet 'WEC Specs').

Generally speaking, the loads on each body are broken down into gravity loads, PTO torque, hydrodynamic loads, joint loads, and mooring loads. The sum of these forces is the total force on the body, and will balance with the inertial loading (e.g. F=ma, see Appendix below for further discussion). All loads are provided in the global coordinate system (note as FRA, or fixed reference system, in the variable name). The PTO torque is also provided in the local system of the nacelle (about the axis of rotation); the PTO torque applied to the arms is simply the equal and opposite of this. All loads are provided at the C.G. of the structure, except for the joint loads, which are provided at the joint location.

Gravity loads are not provided as time series; however, the mass of each body is provided.

The hydrodynamic loads consist of hydrostatic, Froude-Krylov, viscous drag, added mass, and drift forces.

The PTO torque is provided as three separate components, to aid in design. The 'idler' component consists of the friction from the idler bearing (at the port arm / nacelle tube interface). The 'railAndGen' component consists of the generator torque and the friction from rail bearing system. This torque is felt by the drive arm (starboard side), and an equal and opposite torque is felt at the outer housing where the stators connect. The 'mainBear' component consists of main bearings and seals and is felt at the drive arm.

Orientations are provided as Euler angles, in the x-y-z order. The global coordinate system is shown in the SolidWorks model.

In addition to the point loads provided, engineering assumptions will need to be made considering pressure loading. The sea state spectra utilized for simulation are provided; along with the body positions these spectra can be used to calculate the undisturbed wave elevation above any point on the structure at any instance in time.

In addition to consideration of pressure from e.g. depth, several bodies also experience slamming loads as they leave the water and reenter (pontoons, float, float arms, and nacelle). Pressure from these slamming events has been estimated by CPwr, by dividing the hydrodynamic load by the instantaneous cross-sectional area intersected by the undisturbed sea surface. Time series of these pressures are provided. Note that the while the pontoons and nacelle are generally slamming on their lower halves, the float can slam on top or bottom due to its operating on both sides of the nacelle. These slamming pressures were only estimated for extreme seas.

Additional design loads are at the mooring interfaces are specified based on the breaking strength of the mooring lines. This is because the structural interface is required to be stronger than the mooring line (so that in the instance of a mooring failure it is the line that breaks, not the structure). Nominal (0 deg) direction of application of mooring tension is in the x-direction, but the design must accommodate loading over a range about this nominal direction. See mooring load table below for loads and range of application. The mooring interface locations provided were those assumed in modeling; they may be moved, within reason, to accommodate design.

A quality control signal (logical) is also provided for each simulation. Excluded samples (indicated by 'false') are to be applied to all provided signals. The reasons for exclusion include initial ramping in simulation, and 'end stop' activations (a time of $T_z/4$ is excluded following any activation of 'end stop').

The loads as provided have had no safety factors applied. The following PSFs shall be applied to the loads, though other PSFs may be discussed with CPower if applicable standards suggest an alternate.

a. A Partial Safety Factor **(PSF) of 1.5** shall be applied to all loads for design calculations
b. A **PSF of 1.5** shall be applied to all pressures for design calculations
c. A **PSF of 1.1** shall be applied to the mooring loads for design calculations
d. Structural design contractor shall specify a suitable PSF to account for structural uncertainty, as described in "DE-EE0006610 SR-EDR-0100"

	SolidWorks Coordinates					
Mooring interface	**X [m]**	**Y [m]**	**Z [m]**	**Load [kN]**	**Horz [°]**	**Vert [°]**
Bridle (Port)	2.208	10.363	-12.996	1,640	0 +- 30	0 +- 50
Bridle (Stbd)	2.208	-10.363	-12.996	1,640	0 +- 30	0 +- 50
Aft tether	-2.208	0.000	-14.604	2,120	0 +- 90	0 +- 50

4 APPENDIX: BALANCE BETWEEN LOADS AND INERTIA

This appendix is intended to describe how the loads provided for design are calculated from AQWA output, and to demonstrate the balance between loads and inertia.

AQWA reports various loads, such as Froude-Krylov, viscous drag, gravity, etc. The one hydrodynamic load that is not reported is added mass; instead of applying a force, AQWA adjusts the structural mass and inertia in real time to account for added mass. Unfortunately, this is not reported by AQWA.

To provide accurate and balanced loads, CPower first calculated the 6 DOF inertia for each body. Then, all loads that are not applied by the water (i.e. gravity, mooring, joints, PTO) are subtracted from the inertia. What remains is loads applied by water, and is termed 'hydroForceFRA' in the supplied data files.

As is apparent from the method described above, the loads and inertia are balanced for each body (though rounding introduces very small errors in the calculations). However, when a composite body is considered (such as the 'central body' consisting of nacelle, spars, ballast tank, pontoons, and knee braces), the error is somewhat larger.

Keep in mind that in the case of a composite body, CPower is using the calculated inertia for the composite body along with the velocity and acceleration of the composite C.G. Furthermore, loads at C.G.s and joints of sub bodies are translated to the composite C.G. CPower believes that the error is due in part to rounding, but is also related to the way in which AQWA uses fixed joints to keep bodies together. AQWA ensures that the rotational velocities are shared across all the fixed sub bodies, but the positions and accelerations are allowed to drift ever so slightly over time. This ‘drift’ was more pronounced in the float and float arms composite body, which is why it was replaced by a single body in the last iteration of load simulations.

Example figures are shown below for an undamped, 3-hour simulation in extreme seas. The calculated error (or imbalance) between total force and inertia is shown in the time domain, and also as histograms where it is seen that most instances have very small imbalances. Note that the calculated imbalance tends to increase with time for the central body; it is assumed that this is related to the slowly drifting apart of the sub bodies. No histogram is shown for the float body, as the imbalances are so very small anyhow.

The MATLAB code used to calculate the total load, and the inertia term, is provided below.

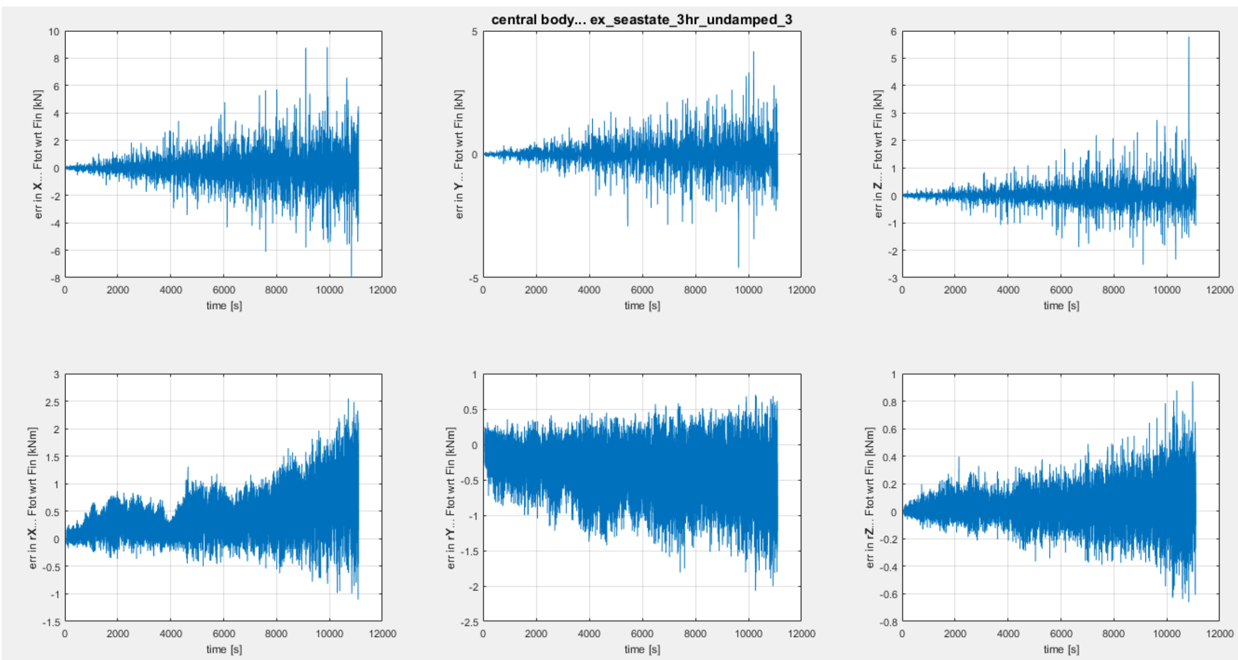

Figure 5 –Time history of load / inertia imbalance for central body.

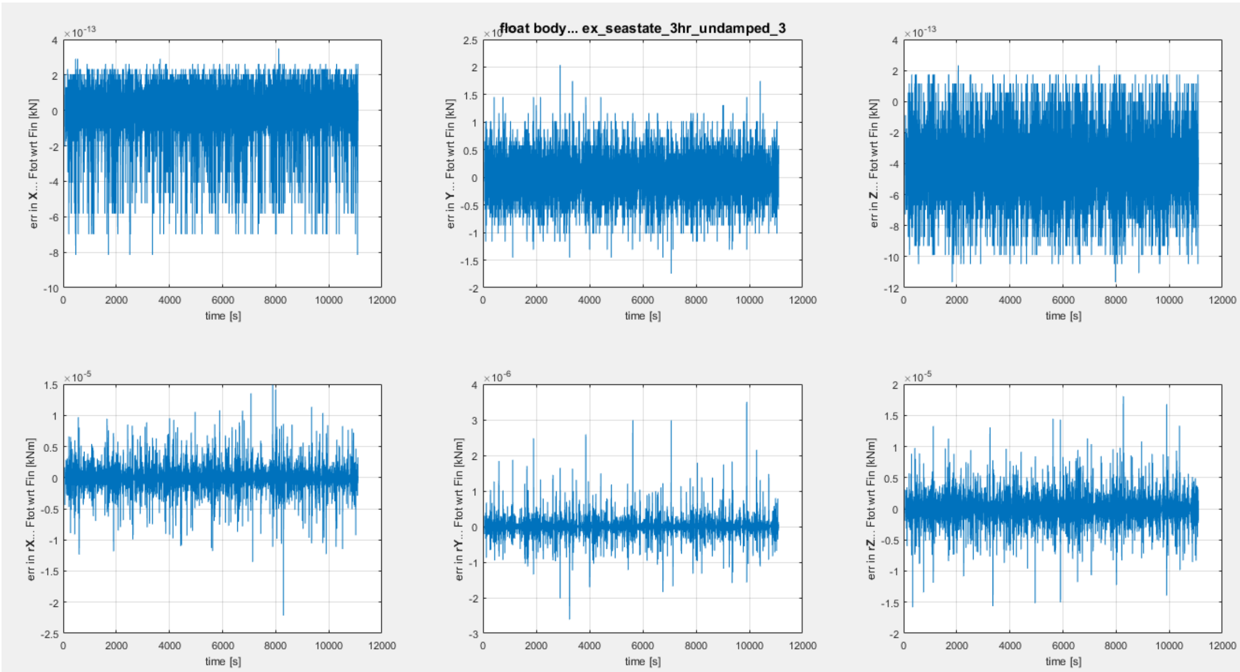

Figure 6 – Time history of load / inertia imbalance for float body.

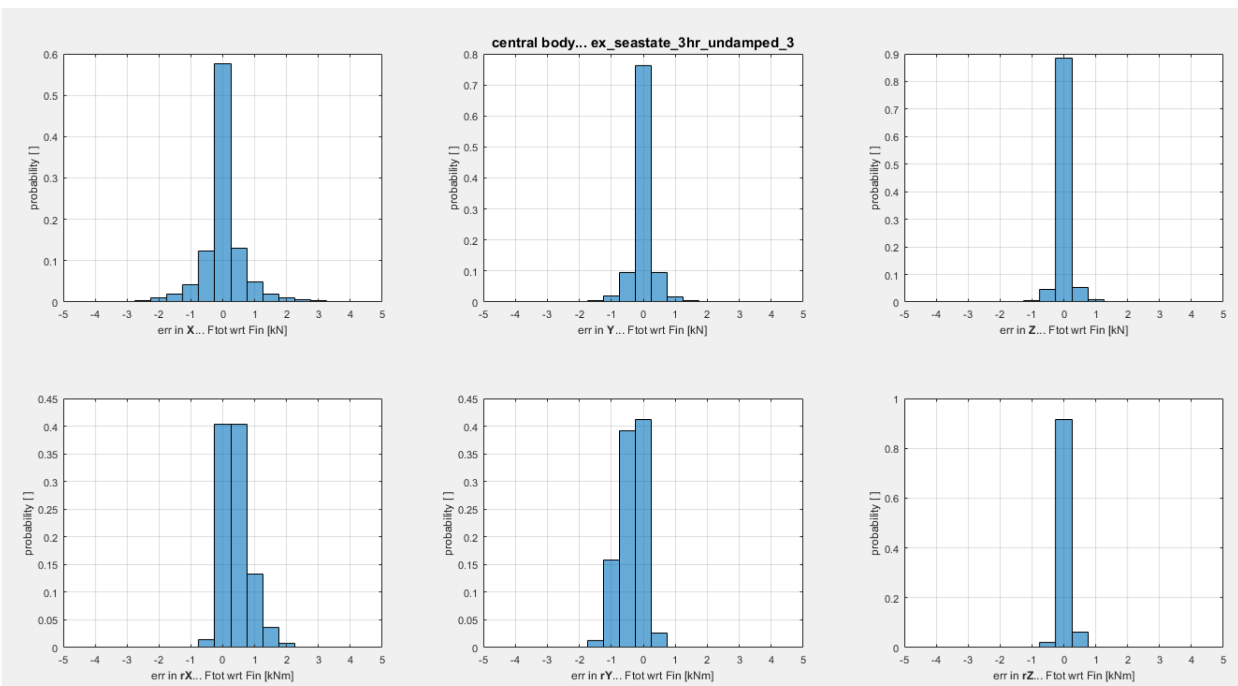

Figure 7 – Histogram of load / inertia imbalance for central body.


```
% testBalance
% load a glosten data set, and check force/acceleration balance
% loads include:
%   hydro, at cg
%   gravity (constant)
%   joints, at joint loc
%   mooring and PTO, at spec'd interfaces

% 6 dof force will be calculated for central body, and float body... and
compared to mass *acc
% central body has
%   hydro and gravity loads for 8 x bodies, as well as mooring, gen, and PTO
'joint' load
% float body has
%   hydro and gravity loads for 2 x bodies, as well as gen, and PTO 'joint'
load

% 3/16/18
% diff body numbering
% float assembly is now 1 body (arms and float combined to one body)

clear
% load simulation results file
filePath='Z:\Engineering\StingRAY V3.3\Design Files\0000 Design Conditions
and Response\newBaselineModel_part2\designInputs_Glosten_20180316_9body\';
fileName='ex_seastate_3hr_bidirectional_damped_1';
load([filePath fileName])

varKeep=who();
varKeep=[varKeep;{'varKeep'}];

%% load specs from excel tables
clearvars('-except',varKeep{:})

% constants
g=9.81; % acc of grav [m/s^2]

% read WEC specs from spreadsheet (joint locations, cg, mooring, inertia)
excelPath='Z:\Engineering\StingRAY V3.3\Design Files\0000 Design Conditions
and Response\newBaselineModel_part2\designInputs_Glosten_20180316_9body\';
excelName='design inputs for Glosten 16mar2018.xlsx';
jointTbl=readtable([excelPath excelName],'Range','I3:Q10','Sheet',2,...
    'ReadVariableNames',false);
jointTbl.Properties.VariableNames={'index' 'jointType' 'strcIndex1' 'strc1'
'strcIndex2' 'strc2' ...
    'x' 'y' 'z'};

cgTbl=readtable([excelPath excelName],'Range','A3:F15','Sheet',2,...
    'ReadVariableNames',false);
cgTbl([11 13],:)=[];
cgTbl(10,2)=cgTbl(10,1);
cgTbl(11,2)=cgTbl(11,1);
cgTbl.Properties.VariableNames={'index' 'strc' 'x' 'y' 'z' 'mass'};
cgTbl.index=[1:9 nan nan]';
```

```
inrtTbl=readtable([excelPath excelName],'Range','A20:H28','Sheet',2,...
    'ReadVariableNames',false);
inrtTbl.Properties.VariableNames={'index' 'strc' 'Ixx' 'Ixy' 'Ixz' 'Iyy'
'Iyz' 'Izz'};

moorTbl=readtable([excelPath excelName],'Range','A33:E36','Sheet',2,...
    'ReadVariableNames',false);
moorTbl.Properties.VariableNames={'index','moor','x','y','z'};

% correct setup for fore in aft configuration
%   in extreme seas it is assumed that the fore float has flipped over to the
aft position
%   the starting position (definition position in AQWA) is different for
arms, float, and joint
cgTbl.x(2)=-cgTbl.x(2);
cgTbl.x(11)=-cgTbl.x(11);

% set up inertia matrix for 9 bodies
inertia=zeros(3,3,9);
for i=1:9
    inertia(1,1,i)=inrtTbl.Ixx(i);
    inertia(2,2,i)=inrtTbl.Iyy(i);
    inertia(3,3,i)=inrtTbl.Izz(i);
    inertia(1,2,i)=inrtTbl.Ixy(i);
    inertia(1,3,i)=inrtTbl.Ixz(i);
    inertia(2,3,i)=inrtTbl.Iyz(i);
    inertia(2,1,i)=inrtTbl.Ixy(i);
    inertia(3,1,i)=inrtTbl.Ixz(i);
    inertia(3,2,i)=inrtTbl.Iyz(i);
end

% inertia matrix for central and float body (only central body now... float
is body 2)
% parallel axis theorem implemented using square of the skew symmetric matrix
constructed from
%   r, the vector from reference point (composite cg) to the components cg

% central body
Ns=[1 3:9]; % indices of bodies comprising 'central body'
Ic=zeros(3,3);
cgc=cgTbl{10,3:5};
for i=1:length(Ns)
    n=Ns(i);
    cg=cgTbl{n,3:5};
    m=cgTbl.mass(n);
    % inertia of singular component
    I=squeeze(inertia(:,:,n));
    % vector from ref point to component cg
    r=cgc-cg;
    % skew symmetric matrix
    rr=[0 -r(3) r(2); r(3) 0 -r(1); -r(2) r(1) 0];
    % parallel axis theorem
    Ic=Ic+(I-m*rr^2);
end

%% specify which body, or composite body to assess
```



```
%   comment out all but one
Ns=2;                % single body, or float assembly (now single body)
bodyName='float body';
Ns=[1 3:9];
bodyName='central body';

if length(Ns)==1
    js=jointsFRA(Ns).jointIndex;        % indices of joints to consider
    I=squeeze(inertia(:,:,Ns));         % inertia
    m=cgTbl.mass(Ns);                   % mass
    cg=cgTbl{Ns,3:5};                   % cg location (def position)
    pos=squeeze(positionFRA(:,:,Ns));   % position of body
    vel=squeeze(velocityFRA(:,:,Ns));   % position of body
    acc=squeeze(accelerationFRA(:,:,Ns));   % acc of body
    posqpr=pos;                         % orientation used for rotation
matrix
else
    js=1;
    I=Ic;       % inertia of central assembly
    cg=cgc;     % cg of central assembly
    m=cgTbl.mass(10);
    pos=centralBodyPositionFRA;
    vel=centralBodyVelocityFRA;
    acc=centralBodyAccelerationFRA;
    posqpr=pos;
end

% rotation matrix is NOT same for all bodies in composite body (because of
euler angles and
%    position drift)
% BUT it will be in FEA so work with this and check error
qpr=nan(3,3,size(pos,2),length(Ns));
for i=1:size(pos,2)
    x=posqpr(4,i);
    y=posqpr(5,i);
    z=posqpr(6,i);
    sx=sin(x);
    sy=sin(y);
    sz=sin(z);
    cx=cos(x);
    cy=cos(y);
    cz=cos(z);

    roll=[cz  -sz 0;...
        sz  cz  0;...
        0   0   1];

    pitch=[cy   0 sy;...
        0   1   0;...
        -sy 0   cy];

    yaw=[1  0   0;...
        0   cx  -sx;...
        0   sx  cx];

    qpr(:,:,i)=roll*pitch*yaw;
```

```
end

% initialize variables for total force and inertia
%   6 dof each, in global axes (FRA) and referenced to cg
Ftot=zeros(6,size(pos,2));
Fin=Ftot;

for i=1:size(pos,2) % loop through time step
    % rotation matrix for this time step
    qpri=squeeze(qpr(:,:,i));

    for ii=1:length(Ns) % loop through sub structures
        n=Ns(ii);

        % translate hydro force to composite cg
        r=qpri*(cgTbl{n,3:5}-cg)';  % vector in FRA from cg of sub structure
to primary cg

        Ftot(1:3,i)=Ftot(1:3,i)+squeeze(hydroForceFRA(1:3,i,n));
        Ftot(4:6,i)=Ftot(4:6,i)+cross(r,squeeze(hydroForceFRA(1:3,i,n)))+ ...
            squeeze(hydroForceFRA(4:6,i,n));

        % translate gravity force to composite cg
        Ftot(1:3,i)=Ftot(1:3,i)+[0;0;-cgTbl.mass(n)*g];
        Ftot(4:6,i)=Ftot(4:6,i)+cross(r,[0;0;-cgTbl.mass(n)*g]);

        % translate joint force to composite cg
        %   only 'end' joints needed (for comp bodies is PTO only)
        jj=jointsFRA(n).jointIndex;
        ji=find(ismember(jj,js));
        for iii=ji'
            jn=jointsFRA(n).jointIndex(iii);
            r=qpri*((jointTbl{jn,7:9}-cg)');    % vector in FRA from joint
location to primary cg
            Fj=squeeze(jointsFRA(n).loads(:,i,iii));
            Ftot(1:3,i)=Ftot(1:3,i)+Fj(1:3);
            Ftot(4:6,i)=Ftot(4:6,i)+cross(r,Fj(1:3))+Fj(4:6);

        end % end joint loop

        % translate PTO torq to composite cg (only for nacelle or float arms)
        if n==1 % nacelle
            PTOtorq=PTOtorqFRA(:,i);
        elseif n==2 % float assembly
            PTOtorq=-PTOtorqFRA(:,i);
        else
            PTOtorq=zeros(6,1);
        end
        Ftot(:,i)=Ftot(:,i)+PTOtorq;

        % translate mooring forces to composite cg (only if ballast tank)
        if n==4 % ballast tank
            for iii=1:4
                Fm=squeeze(mooringFRA(:,i,iii));
```

```
                r=qpri*((moorTbl{iii,3:5}-cg)'); % vector in FRA from mooring
lines to primary cg
                Ftot(1:3,i)=Ftot(1:3,i)+Fm;
                Ftot(4:6,i)=Ftot(4:6,i)+cross(r,Fm);
            end
        end

    end % end body loop

    %%% calc mass times acc term
    % translational inertia
    Fin(1:3,i)=m*acc(1:3,i);
    % rotate inertia matrix to FRA
    Iin=qpri*I*qpri';
    % rotational inertia
    Fin(4:6,i)=Iin*acc(4:6,i)+cross(vel(4:6,i),Iin*vel(4:6,i));

end

plusFig=12;
normIt=0;
dofNames={'X' 'Y' 'Z' 'rX' 'rY' 'rZ'};
figure(1+plusFig);clf
for dof=1:6
    if normIt
        rmsSignal=rms((Ftot(dof,qcIndex)+Fin(dof,qcIndex))/2);
        uText=', norm by rms(Ftot)';
        if dof<=3
            binMe=-5.25:0.5:5.25;
        else
            binMe=-5.25:0.5:5.25;
        end
    else
        rmsSignal=1e3;
        if dof<=3
            uText=' [kN]';
            binMe=-4.75:0.5:4.75;
        else
            uText=' [kNm]';
            binMe=-4.75:0.5:4.75;
        end
    end
    figure(1+plusFig)
    subplot(2,3,dof)
    plot(time(qcIndex),(Ftot(dof,qcIndex)-Fin(dof,qcIndex))/rmsSignal)
    set(gca,'fontSize',8)
    xlabel('time [s]')
    ylabel(['err in \bf' dofNames{dof} '\rm... Ftot wrt Fin' uText])
    grid on

    figure(2+plusFig)
    subplot(2,3,dof)
    histogram((Ftot(dof,qcIndex)-
Fin(dof,qcIndex))/rmsSignal,binMe,'normalization','probability')
    set(gca,'fontSize',8)
    xlabel(['err in \bf' dofNames{dof} '\rm... Ftot wrt Fin' uText])
```

```
    ylabel('probability [ ]')
    grid on
    set(gca,'xtick',-5:1:5)

end

figure(1+plusFig)
supertitle([bodyName '... ' fileName],'interpreter','none')

figure(2+plusFig)
supertitle([bodyName '... ' fileName],'interpreter','none')
```

