Programme Area: Marine

Project: PerAWAT

Title: User Report for the SpecWEC Modelling Tool - Part 2

Abstract:

This document contains the User Report for the SpecWEC modelling tool. The methodology for using the SpecWEC modelling tool is summarised along with instructions for using the final release and recommendations about best practice when using it. The production and interpretation of results from the SpecWEC modelling tool is also addressed, as are the applications and limitations of the SpecWEC modelling tool. Results from the verification and validation of the tool (from WG1 WP2 D4 and D5) are summarized, where it is shown that, when averaged over the array and all sea states, agreement for power capture between a potential flow model and the SpecWEC modelling tool is better than 9%, and the agreement between experimental wave tank data and the SpecWEC modelling tool is better than 12%. SpecWEC is most suitable for estimating the energy production of a WEC array. Because of the computational efficiency of SpecWEC relative to other phase-resolving WEC array models it can be used to investigate multiple layouts and sea-states to produce estimates of their relative annual average power production. The key limitation of SpecWEC is that it does not produce any phase-dependent information, so that it can only be used for estimating the average expected performance of a WEC array, not the temporal variation of parameters or the extreme values.

Context:

The Performance Assessment of Wave and Tidal Array Systems (PerAWaT) project, launched in October 2009 with £8m of ETI investment. The project delivered validated, commercial software tools capable of significantly reducing the levels of uncertainty associated with predicting the energy yield of major wave and tidal stream energy arrays. It also produced information that will help reduce commercial risk of future large scale wave and tidal array developments.

User Report for the SpecWEC modelling tool

WG1 WP2 D8 Part 2

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CONTENTS

Executive summary

This document contains the User Report for the SpecWEC modelling tool, which is part of WG1 WP2 D8. This report begins with an introduction that includes the scope of the document, lists the relationship of this report to other deliverables, and lists the acceptance criteria for this document. The methodology for using the SpecWEC modelling tool is then summarized in Section 2. The methodology consists of a series of steps the user must take to use the tool, and includes recommendations about best practices for these steps. A summary of the full methodology is presented here, with the full methodology being found in WG1 WP2 D6.

Instructions for using the final release of SpecWEC are presented in Section 3. The files provided with the final release are described. Then, it is explained that the user can either run the model as it is, using one of the two built-in representations for WECs, or that they can create their own representation. Details on how to create a WEC representation are given, followed by a description of how to create an executable file to run the model using the new WEC representation. Next, the process for running the model is described, including a description of how to create the files needed to use the built in WEC representations. Finally, a way for the user to use any boundary frequency spectrum is described.

In section 4, the production and interpretation of results from the SpecWEC modelling tool is addressed. It is described how to output standard useful variables in the TOMAWAC model (such as significant wave height and spectral energy density). Outputs relating specifically to the wave energy devices (such as power output and displacement) are also described. This is followed by a discussion of how to interpret array outputs, depending on what the key objectives of the study are.

Finally, the applications and limitations of the SpecWEC modelling tool are discussed. Results from the verification and validation of the tool (from WG1 WP2 D4 and D5) are summarized. It is shown that, when averaged over the array and all sea states, agreement for power capture between a potential flow model and the SpecWEC modelling tool is better than 9%, and the agreement between experimental wave tank data and the SpecWEC modelling tool is better than 12%.

SpecWEC is most suitable for estimating the energy production of a WEC array. Because of the computational efficiency of SpecWEC relative to other phase-resolving WEC array models it can be used to investigate multiple layouts and sea-states to produce estimates of their relative annual average power production.

The key limitation of SpecWEC is that it does not produce any phase-dependent information, so that it can only be used for estimating the average expected performance of a WEC array, not the temporal variation of parameters or the extreme values. The current implementation is also limited in that diffraction by the WECs in the array is not modelled and that the WEC model requires

calibration. It is expected that both of these limitations will be eliminated (or significantly reduced) in future releases.

1 Introduction

1.1 Scope of this document

The purpose of this document is to provide guidance for users of the SpecWEC (Spectral representation of a Wave Energy Converter) tool. Section 2 contains the methodology, which describes the choices the user must make and provides suggestions on how to make the best possible choices. Section 3 contains the details of how to implement the model, and Section 4 contains guidance for interpreting and presenting the results. Finally, the applications and limitations of the SpecWEC model are included in Section 5.

1.2 Relationship to other deliverables

This user report is part of WG1 WP2 D8, which also includes a scientific report and the final release of the SpecWEC software. The representation and implementation in the SpecWEC tool were described in WG1 WP2 D1 and D2, respectively. The beta release of the SpecWEC tool was WG1 WP2 D3. SpecWEC was compared with other numerical models in WG1 WP2 D4 and with experimental wave tank data in WG1 WP2 D5.

1.3 WG1 WP2 D8 Acceptance criteria

The acceptance criteria for the user report in WG1 WP2 D8 states that it should describe all the data input requirements, methodology for using the software, and guidance on producing and interpreting the results. The user report should be of sufficient detail that all logical steps can be understood and followed by a third party. The user report will describe the software limitations and applications. The methodology is included in the next section of the report, the data input requirements in Section 3, guidance for interpreting and producing results in Section 4, and the limitations and applications in Section 5.

2 Methodology

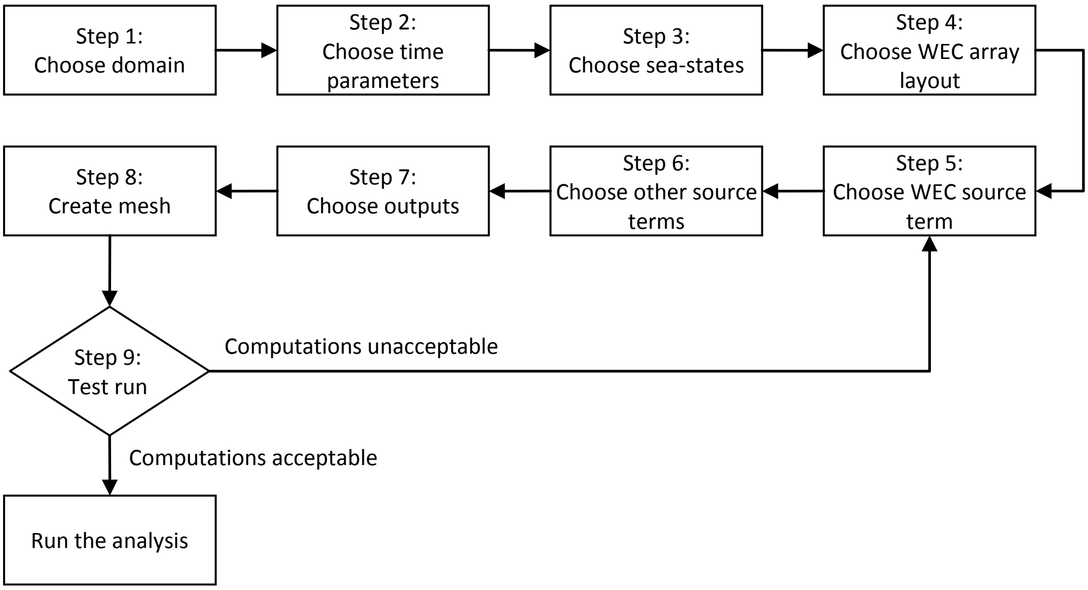
The SpecWEC tool is an add-on for the spectral wave model TOMAWAC that allows for the modelling of arrays of wave energy converters. Users of SpecWEC should first familiarize themselves with the use of TOMAWAC and be competent in using TOMAWAC for the modelling of wave transformations in general. TOMAWAC is an open-source software package, which is part of the TELEMAC suite originally developed by EDF. The software and manuals can be found at the http://www.opentelemac.org/ - to download you must register with the TELEMAC-MASCARET community. This User Report should be read in conjunction with the TOMAWAC manual (EDF 2011), which provides a significant amount of background information that is not replicated in this document.

The SpecWEC tool is primarily designed to be used for the prediction of power output of individual WECs in an array, but can also be used to examine the effect of a WEC array on the surrounding wave climate. The following methodology consists of a series of recommended steps for users of the SpecWEC tool. It is designed to walk users through all the decisions they must make in the process of setting up a SpecWEC model run, giving recommendations on how to make the most appropriate choices.

There are several input files for the TOMAWAC model that define the mesh, the boundary conditions, and other parameters needed for the model runs. Details on how these files need to be constructed for SpecWEC are described in the methodology; the required syntax for most of these files can be found in the TOMAWAC user manual. Specifically the files are:

1. **Case file** - a text file that lists all the basic parameters needed for a model run, including time step, initial and boundary spectra, duration of run, and number of frequency and direction components. Syntax can be found in the TOMAWAC user manual (EDF 2011).
2. **Mesh geometry file** - a binary file that contains the information about nodes and mesh elements. Must be generated in Selafin, the file format specific to the TELEMAC model system (EDF 2010) . Selafin uses a binary format which can be generated using Blue Kenue (Canadian Hydraulics Centre 2010), which can be downloaded at: http://www.nrc-cnrc.gc.ca/eng/solutions/advisory/blue_kenue_index.html.
3. **Mesh boundary conditions file** - a text file that contains a list of all the boundary nodes of the mesh and their boundary condition settings. Syntax can be found in the TOMAWAC user manual (EDF 2011).
4. **WEC information file** (wecinfo.txt) - a text file specific to SpecWEC that contains information about the WECs including location and any performance coefficients. Syntax can be found in Section 3.

The following diagram illustrates the steps of the methodology. It is recommended that the user first completes all the steps up to and including creating the mesh (Step 8). Once the mesh has been created, the user should perform a test run with the designated mesh, sea states, and time step and model run duration. This will allow the user to make an estimate of how long all of their desired runs will take. If the computation time is too long, the user may wish to decrease the spatial resolution of the mesh and/or increase the time step length (ensuring that the Courant number is still acceptable) or consider other methods by which the computational time can be made acceptable whilst producing the desired output. At this point the user can also perform some tests in order to verify that the model run-time parameters and WEC inputs are reasonable. The user should iterate this process until suitable parameters are found, and then proceed with their analysis.



A complete description of each of the steps in the methodology together with a worked example for modelling a wave farm can be found in WG1 WP2 D6/7. A brief description is provided here for clarity.

1. **Choose domain and boundary conditions:** The domain may be of any size that the user chooses. The bathymetry and coastline data sets are required for this step. Boundary conditions can either be fixed, in which a set spectra is imparted on the boundary, or open, in which energy flows freely across the boundary. When using fixed boundary conditions, the user must be careful to account for the effects of directional spreading of the ocean waves near the boundaries as well as possible variation of the spectrum along the length of the boundary.
2. **Choose time step and length of simulation:** The time step for the simulation can be chosen with a simple calculation involving the target Courant number (a maximum value of 2.0 is suggested), the maximum group speed of the waves, and the desired spatial resolution of the mesh. The length of the simulation can be determined with a simple calculation involving the size of the domain and the minimum group speed of the waves.
3. **Designate sea state:** The standard TOMAWAC model only allows the user to input sea state parameters as a JONSWAP spectrum (see for example Holthuijsen 2007 pg 160) , based on significant wave height,peak period and the bandwidth parameter. The SpecWEC tool includes a modification that allows the user to read in any frequency/directional spectrum and apply it along the boundaries.

4. **Choose WEC array configuration:** There is no limit to the number of WECs that can be included for a simulation. They must be spaced so that there are a sufficient number of computational nodes between WECs, depending on the desired grid resolution. The need for computational nodes between the WECs is to allow the effect of the directional discretization of the wave action propagation to reduce. Typically this was found to require 3-6 nodes – with more nodes required for highly directional sea-states.
5. **Choose WEC source term:** There are currently three ways for the user to represent a WEC in SpecWEC. A simple linear frequency and directional dependent representation and a heaving point absorber representation are included. Additionally, the user may write a bespoke representation for a specific WEC; a sample subroutine shell is provided to support this option.
6. **Choose other source terms:** There are several source terms that can be turned on and off in TOMAWAC to represent physical mechanisms such as wind input, white-capping, bottom friction dissipation, and others. The user should follow the recommendations found in the TOMAWAC manual.
7. **Choose outputs:** TOMAWAC can output any number of two dimensional variables that describe the wave field, including significant wave height. The full frequency directional spectrum can also be output at any point in the domain. The included WEC representations automatically output the power absorbed by the devices.
8. **Create mesh:** The user must generate a mesh file in the Selafin binary format and a boundary condition text file. The open source BlueKenue program can be used for this, as well as the MATISSE meshing program that is bundled with the TELEMAC system. It is recommended that the user set the WEC locations as hard points in the mesh, and use variable node density to decrease computational time. In general finer mesh resolutions will produce more accurate results; however, care must be taken to ensure that the mesh is not so small that at any particular frequency more energy is extracted by the WEC than available in the waves incident on the node. Thus, this will depend on both the mesh resolution and the characteristics of the WEC. A reasonable first estimate would be a typical node spacing of 25 – 50 metres.
9. **Perform a test run:** The user should then perform a test run to check that all the parameters are correct and that the computational time is acceptable. A specified range of checks should be carried out to verify that the time step, duration of simulation, and WEC representation are acceptable.

3 Final Release User Instructions

This section contains the instructions for using the SpecWec final release. It does not contain instructions for running the base TOMAWAC model - these can be found on the EDF website: http://www.opentelemac.org/[1]. The final release includes executable files, as well as all of the Fortran source files, object files, and library files needed for running SpecWEC. The user has two options. If they choose to use one of the two provided WEC source representations (the linear frequency directional dependent representation or the heaving point absorber representation), then the provided executable file can be placed in the same directory as the input files and the model can be run, as described in Section 3.3. Alternatively, if a bespoke WEC representation is required, this must first be written and saved as a dynamic link library, as described in Section 3.1. They would then need to create an executable using this ‘dll’, as described in Section 3.2. Finally, they would put the executable in the same directory as the input files and run it as described in Section 3.3.

The SpecWec final release includes five folders:

1. *tomawac source code* : contains the source Fortran files for the modified TOMAWAC model and the compiled object files for those same Fortran files
2. *tomawac libraries:* contains some library files needed to run TOMAWAC
3. *WEC subroutines*: contains the subroutines available for the representation of wave energy converters in TOMAWAC.
4. *runtime*: contains two files needed for running SpecWec
    a. *WACDICO*: a dictionary file containing keywords used for reading in the case file
    b. *CONFIG*: a file that sets the language of the simulation to English
5. *examples*: contains two folders with example input and output files
    a. *linear*: contains a simple rectangular regular mesh file, boundary conditions file, case file, WEC information file (wecinfo.txt), and output spectra, significant wave height, and power output files for an example using the linear representation of wave energy converters
    b. *point absorber*: contains a simple rectangular regular mesh file, boundary conditions file, case file, WEC information file (wecinfo.txt), and output spectra, significant wave height, and power output files for an example using the point absorber representation

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[1] Please note that at this location the manuals are available in both English and French, and can typically be distinguished by the use of English or French words in the filename.

3.1 Writing your own WEC source term subroutine

When the source term for a wave energy converter cannot be represented using the standard subroutines, the user can write their own WEC source term subroutine, which may contain whatever calculations are necessary to correctly model the dynamics and hydrodynamics of the WEC. This subroutine is only called for the nodes that contain a WEC. To support the production of the WEC source term subroutine, a shell script is provided in the *WEC subroutines* folder that can be modified as required. The shell script contains the necessary subroutine definition as well as the code required to make the subroutine into a dynamic link library. The variables which make up the argument of the subroutine are described in detail in the shell script, which can be found in Appendix A of this document. Further guidance on how to write the WEC subroutine can be examining the subroutines for the two current WEC representations, which can be found in the *WEC subroutines* folder.

In writing the WEC subroutine there are two variables which are particularly important: *TSTOT* and *TSDER*. These variables contain the frequency and directionally dependent source term strength at each node in the model for the TOMAWAC calculation and they must be modified with the WEC source term strength. Thus, the variables are three dimensional with the indices are node, frequency and direction. Please note that these variables cannot be written over; instead the WEC source term strength must be added to them. If *S* is the WEC source term strength, then the subroutine must contain a statement which looks like: *TSTOT = TSTOT+S*. The two variables are known as the total source term strength (*TSTOT*) and the partial source term strength (*TSDER)*. There are two source term strength variables because of the way in which TOMAWAC calculates the various ocean energy source terms. The source terms are assumed to be dependent on the wave energy density spectrum, and the *TSDER* variable represents the source term strength after a derivative with respect to that energy spectrum has been taken. A full explanation of these variables can be found in Section 6.3 of the TOMAWAC manual. The simplest way to deal with these two variables as far as WEC source term strength is concerned is to set the *TSTOT* variable to the total calculated WEC source term strength and not to modify the *TSDER* variable.

Not modifying the *TSDER* variable is equivalent to using an explicit scheme for the WEC source term. The advantage of setting *TSDER* is that an implicit scheme can be used for the WEC source term, which allows larger time steps to be used without generating issues with stability of the solution. In many cases it may be possible to estimate the required modification to the *TSDER* variable, which will increase the solution stability; however, it is not essential. Current experience suggests that it is not typically necessary to modify the *TSDER* variable to maintain solution stability and this simplifies the production of the sub-routine. However, the user is free to modify the *TSDER* variable where the derivative of the source term is known.

Once the source term subroutine has been written, it must be compiled with a Fortran compiler as a dynamic link library; this process creates two files which have the same names regardless of what the Fortran file is called. One is the *WECSOURCE.dll* file used at runtime and the other is the *WECSOURCE.lib* file which is linked into the SpecWec executable.

3.2 Creating the SpecWec executable

In order to create the TOMAWAC executable, the user must use a Fortran linker/compiler to link together the following items:

1. All of the object files in the *tomawac source code/object files* folder
2. All of the library files in the *tomawac libraries* folder
3. The desired *WECSOURCE.lib* file.
    a. This file corresponds to the user-chosen WEC source term dynamic link library for the wave energy converter to be modelled. For example, if the user wishes to use the provided point absorber source term subroutine, they must include the file *WECSOURCE.lib* found in the *WEC subroutines/point absorber* folder.

Please note that when performing this linking step to create the TOMAWAC executable, it is important to use the TOMAWAC linker options in order for the model to work properly. These can be found in the TOMAWAC model documentation. In particular, the stack size must be set to 61708864. To achieve this for the Intel Visual Fortran compiler (which was used to create the executables, object files, and libraries included with the final release), the linking statement that creates the executable should include the following segment: */link /stack:61708864*.

3.3 Running SpecWec

Once the executable has been created, SpecWec can be run. To run SpecWEC successfully there are several files which need to be present with specific names in the directory in which SpecWec is to be run. These include:

1. *CONFIG*: a file found in the *runtime* folder of the final release
2. *WACDICO*: the TOMAWAC library file, found in the *runtime* folder of the final release
3. *WACCAS*: the case or steering file for the TOMAWAC model run, written by the user as per the TOMAWAC instructions. In order for the SpecWec tool to be activated, the *CONSIDERATION OF WECs* key word in the case file must be set to *1, YES,* or *TRUE*.

4. *WACGEO*: the geometry file containing information about the mesh, created by the user following the instructions in the TOMAWAC user manual
5. *WACCLI*: the boundary conditions file, created by the user following the instructions in the TOMAWAC user manual
6. *WECSOURCE.dll*: the dynamic link library containing the WEC source term strength subroutine
7. *Any additional files required by the WECSOURCE subroutine*: for example the point absorber and simplified linear subroutines require an additional input file called *wecinfo.txt*.
8. The executable file

   Provided that all these files are placed in the same directory (referenced here as the Running Directory), SpecWEC will run successfully. This can be achieved by using the command line to call the SpecWEC executable.
9. *specin.txt*: this file is optional, and contains the spectral wave energy density if the user wishes to input a specific spectrum. See details in Section 3.4.

3.3.1 Using the simplified linear WEC subroutine

If the user wishes to implement the simplified linear WEC subroutine, they can either use the provided executable file or link in the *WECSOURCE.lib* file found in the *WEC Subroutines/linear* folder of the final release during the creation of the executable. Then, one additional text file must be created to input information about the WECs to SpecWec. This file must be called *wecinfo.txt*, and must contain certain information in the correct order. However, this information can be separated by comments (denoted by the "!" symbol to the left of any comments) to enhance readability. The information required, in order is:

Number of WECs			
WEC location format	Note: use 1 to define the WEC locations using node numbers and 2 using (x,y) positions in metres		
WEC orientation (θ_0)	Note: the WEC orientation must be defined in radians		
Number of output variables	Note: this must be set equal to the number of computational frequencies		
Number of WEC parameters	Note: this must always be set to 3		
WEC location 1: node number 2: (x,y) position	**μ** (ratio of the inertial and radiation forces)	**λ** (ratio of the applied to radiation damping)	Natural frequency of the WEC (Hz)

See Section 4.1.1 of the scientific report for a detailed description of the parameters **λ, μ,** and $\boldsymbol{\theta_0}$. For example, if there is one WEC located at node 100 with a WEC orientation of 0 radians, **μ** and

λ values of 1, a natural frequency of .1 Hz, and the computation has 30 frequency points, then the input file will look as follows:

```
! Number of WECs
1
! WEC Location format
1
! WEC orientation
0
! Number of output variables
30
! Number of WEC parameters
3
! List of WEC location and parameters
100   1   1   0.1
```

Once this input file has been written, it should be placed in the running directory for SpecWec with the other SpecWec input files and then the model can be run. There will be one output file generated specifically by this subroutine (in addition to any standard TOMAWAC output requested by the user). This output file, *wecout.txt* contains the following information printed out at each time step:

Node number	X location of node	Y location of node	Power absorbed at first frequency	....	Power absorbed at last frequency

The amount of power absorbed by each WEC is summed over all directions and then reported for each frequency at each time step in Watts.

Included in the final release is a set of example files for using the simplified linear subroutine. The mesh file (rectangular.geo) includes a rectangular mesh with dimensions 1.5 km by 4.5 km with a spatial resolution of 25 metres. A Jonswap spectrum with significant wave height of 2 m, energy period of 9 seconds, directional spreading parameter s of 15 with waves travelling east is applied on the north, west, and south boundaries in the boundary condition file (boundary.cli). The time step and other parameters are set in the case file (case.txt). There is an array of 100 WECs in five staggered rows of twenty devices, with a spacing of 100 metres. The WEC parameters are given in the wecinfo.txt file. An output file containing the full frequency directional spectra at the WEC locations is given in output.spec. The significant wave height is given in the hs.slf file. Finally, the power output is given in the wecout.txt file. The input files can be placed in the Running Directory (as described in Section 3.3) and the executable run. The user can then compare the output files they generate with the provided output files to ensure that their model is working correctly.

3.3.2 Using the point absorber subroutine

If the user wishes to implement the point absorber subroutine, they can use the provided executable or link in the *WECSOURCE.lib* file found in the *WEC Subroutines/point absorber* folder of the final release during the creation of the executable. Then, one additional text file must be created to input information about the WECs to SpecWec. This file must be called *wecinfo.txt*, and must contain certain information in the correct order. However, this information can be separated by comments (denoted by !) to enhance readability. The information required, in order is:

Number of WECs		
WEC location format	Note: (1 for nodes, 2 for (x,y) positions)	
Hydrostatic Stiffness (**C**)	Units: N/m	
Body Mass (**M**)	Units: kg	
Number of output variables	Note: must be equal to the number of computational frequencies	
Number of power take off parameters	Note: this must always be set to 1	
WEC location	This is a list of the WEC locations for each WEC in the computation	
Added mass (**A**) for the first computational frequency Units: kg	Added damping coefficient (**B**) for the first computational frequency Units: Ns/m	Exciting force coefficient (**K**) for the first computational frequency Units: N/m
Added mass (**A**) for the second computational frequency	Added damping coefficient (**B**) for the second computational frequency	Exciting force coefficient (**K**) for the second computational frequency
...	...	...
Added mass (**A**) for the last computational frequency	Added damping coefficient (**B**) for the last computational frequency	Exciting force coefficient (**K**) for the last computational frequency
Power take off values for each device $\boldsymbol{\Lambda}$ for the linear PTO coefficient or $\boldsymbol{F_{PTO}}$ for the Coulomb friction force	Linear power takeoff damping coefficient: units in Ns/m Coulomb friction: units in Newtons	
Damping flag	Note: 1 for Coulomb friction, 2 for linear power take off	
Area over which power is absorbed	Units: metres squared	
Upstream nodes	This is a list of the upstream nodes corresponding to the WEC locations.	

The hydrostatic stiffness, added mass, added damping, and exciting force can be obtained from a potential flow model such as WAMIT (WAMIT 2011), or otherwise generated by whatever means the user considers adequate. The upstream nodes are defined as the nearest computational nodes to the WEC that are located upstream from the WEC. These can be determined once the mesh has been designed. If different wave directions are used for the boundary spectra, then the upstream nodes may change. For a small number of WEC nodes, the upstream nodes may be determined visually using the Blue Kenue program. For a large number of nodes, it may be done programmatically by interrogation of the node locations. The list of upstream nodes is used in SpecWEC to determine the incident wave energy spectra for the WECs. The area of which power is absorbed can be determined using an iterative implementation of the divergence theorem. See section 3.2 of the scientific report for a complete description of the required parameters. An example wecinfo.txt file for 10 sample point absorbers has been included in Appendix B of this document.

Determination of the area over which power is absorbed must be carried out before any SpecWEC runs with arrays of devices can be done. The point absorber subroutine calculates the power absorbed for each WEC device, in units of W. However, the quantity that is changed in the TOMAWAC model to represent the presence of the WEC is the spectral wave energy density, in units of W/m^2. Therefore, the area over which the energy is removed must be specified. This is done using the divergence theorem, which states:

$$\iint_A \nabla \cdot F dA = \oint F \cdot \vec{n} dl = P_{abs}$$

In words, this formula shows that the integral of the divergence of a vector quantity over an area (which is a measure of the strength of the sources and sinks of that vector quantity within the area and therefore the power absorbed by the device) is equal to the integral over a closed path of the vector quantity dotted with the normal to that path. For this analysis, we use the wave energy flux as the vector quantity. This is defined as:

$$F \equiv E\overrightarrow{c_g},$$

where E is the wave energy spectral density and c_g is the wave group speed.

For the iterative process, the wave energy flux is calculated on a closed path around a single WEC node:

$$\oint E\overrightarrow{c_g} \cdot \vec{n} dl$$

This value can then be compared with the power absorbed calculated by SpecWEC. When those numbers match, then the correct area has been determined. Note that when the grid is regular (consisting of identical triangles), then the area will be the same for each node, and the iterative process only needs to be carried out once. It is recommended that the closed path used be a rectangle or square because numerical spatial diffusion results in non-physical dispersion of the energy flux. If a circle is used, as would seem appropriate, then the energy flux normal to the circular path is not conserved because the energy is diffused spatially without changing direction. However, a rectangular path is not sensitive to this type of numerical diffusion.

In order to implement this iterative process, the user must follow these steps:

1. Run SpecWEC with a representative sea state and a WEC located only at one node. The computational mesh should be the one that will be used for the array analysis. Any nonzero value can be used for the area for the initial run. A flat bottom should be used for the bathymetry. The wave energy spectra should be output at several nodes which form a closed square or rectangle around the WEC node. The TOMAWAC model has a limit of 99 wave energy output spectra for each run, so the user should take this into account when designing the mesh. It is recommended that a regular grid is used, for two reasons. The area over which the power is absorbed will be the same for each node in a regular grid. And, it is easy to form a square of nodes around the test node when a regular grid is used.
2. Calculate the energy flux around the node using the divergence theorem. This is done by using the wave spectra output at the nodes on the square. Because the wave energy density is not only a function of space, but also frequency and direction, it must be integrated in frequency and direction too. The way this is done is to calculate first the group speed as a function of frequency and direction and then dot that vector with the normal vector. The group speed can be determined from the computational frequencies used for the model run. Then the energy density is multiplied by the normal group speed (determined from the computational frequencies used for the model). Next, the resulting quantity is integrated in direction, then frequency, and finally around the closed path.
3. Compare the integrated energy flux to the power absorbed.
4. Adjust the area according to the results of Step 3. If the integrated energy flux is too large, then too much energy is being removed. The area should be increased. If the integrated energy flux is smaller than the power absorbed, not enough energy is being taken out. The area should be decreased. The area to be used can be determined using a linear interpolation once two iterations have been completed. By assuming an inverse relationship between the energy flux and the area, the target area can be calculated by interpolation using the reciprocal of the areas and energy fluxes from the first two iterations with the desired power absorbed as the target energy flux.
5. Repeat steps 1-4 until the integrated energy flux and the power absorbed agree with in a pre-chosen tolerance level (recommended 1%).

An example set of iterations is provided in the table below.

	Iteration 1	Iteration 2	Iteration 3
Target power absorbed	50 kW	50 kW	50 kW
Representative area	452 m^2	377 m^2	386 m^2
Energy flux deficit	39.1 kW	52.3 kW	49.9 kW
Power absorbed / Energy flux deficit	1.279	0.956	1.002

Once the input file has been written, it should be placed in the running directory for SpecWec with the other SpecWec input files and then the model can be run. There will be four output files generated specifically by this subroutine (in addition to any standard TOMAWAC output requested by the user). The first output file, *powout.txt* contains the following information printed out at each time step:

Node number	X location of node	Y location of node	Power absorbed at first frequency	....	Power absorbed at last frequency

The amount of power absorbed by each WEC is summed over all directions and then reported for each frequency at each time step in Watts.

The second output file, *displout.txt* contains the same format as the *powout.txt* file, but has the standard deviation of the displacement (as a function of frequency) in metres. The structure is as follows:

Node number	X location of node	Y location of node	STD of displacement at first frequency	....	STD of displacement at last frequency

The third output file, *radout.txt* contains the radiated power in Watts. It also has the same structure as the other output files:

Node number	X location of node	Y location of node	Power radiated at first frequency	....	Power radiated at last frequency

Finally, the output file *dampingout.txt* contains the linearised PTO coefficient used. When the user has designated the linear PTO coefficient, this file simply returns the input value. However, when the user has designated the Coulomb friction PTO algorithm, this output contains the quasi-linear

PTO coefficient that was calculated during the Coulomb friction iteration calculation (as described in Section 3.2.6 of the Scientific Report). The structure of the *dampingout.txt* file is as follows:

Node number	X location of node	Y location of node	PTO coefficient

Included in the final release is a set of example files for using the point absorber linear subroutine. The mesh file (rectangular.geo) includes a rectangular mesh with dimensions 1.5 km by 4.5 km with a spatial resolution of 25 metres. A Jonswap spectrum with significant wave height of 2 m, energy period of 9 seconds, directional spreading parameter s of 15 with waves travelling east is applied on the north, west, and south boundaries in the boundary condition file (boundary.cli). The time step and other parameters are set in the case file (case.txt). There is an array of 100 WECs in five staggered rows of twenty devices, with a spacing of 100 metres. The WEC parameters are given in the wecinfo.txt file. The details for the heaving buoy point absorbers are the same as were used for verification of SpecWEC (in WG1 WP2 D4 and D5) and in the site case example of SpecWEC (WG1 WP2 D7). An output file containing the full frequency directional spectra at the WEC locations is given in output.spec. The significant wave height is given in the hs.slf file. The power, displacement, radiation, and damping output are given in the powout.txt, displout.txt, radout.txt, and dampingout.txt files respectively. The input files can be placed in the Running Directory (as described in Section 3.3) and then the SpecWEC executable run. The user can then compare the output files they generate with the provided output files to ensure that their model is working correctly.

3.4 Reading in spectra from file

As part of the SpecWEC modification of TOMAWAC, the user does not have to use Jonswap spectra for the boundary conditions (as in TOMAWAC), but may read in any frequency spectra they like from a text file. In order to use this option, the following line must be added to the case file[2]:

LIMIT SPECTRUM MODIFIED BY USER = YES

The user must then place an additional file, titled *specin.txt*, into the Running Directory. *specin.txt* is a text file containing the desired spectral energy density, listed as a function of frequency and direction at each fixed boundary point. Those frequencies and directions must correspond to the computational frequencies and directions set by the user for the TOMAWAC model. The spectra can also vary along the boundary, if the user chooses. The *specin.txt* file should contain the spectral wave energy density in $m^2Hz^{-1}rad^{-1}$. This quantity should be in a list with one

---

[2] the location of the line in the file does not matter

value per line, listed by frequency and direction for each point on the boundary. The boundary points should be listed in the same order as those in the WACCLI boundary conditions file. For example, if the user has 20 computation frequencies, 10 computational directions, and 100 boundary points, and the energy density spectrum is stored in the variable F with a size of (20,10,100), the following Matlab code will generate the *specin.txt* file:

```
fid = fopen('specin.txt','w');
for ii = 1:20
   for jj = 1:10
         for kk = 1:100
               fprintf(fid,'%12.6f\n',F(ii,jj,kk));
         end
   end
end
fclose(fid)
```

4 Producing and interpreting results

Once the user has completed the desired model runs, they will need to visualize and interpret their results. There are two different classes of outputs to deal with: ocean wave spectral information produced by TOMAWAC, and wave energy device information produced by the SpecWEC tool. These outputs are discussed separately in the following sections.

4.1 TOMAWAC outputs

There are two different kinds of output that can be created by the TOMAWAC model. The first are two dimensional variables that are output at each point on the computational mesh, and include significant wave height, variance, and peak frequency. These variables can be output by adding a line to the model run case file that specifies which variables are desired as output. For example, if the user wishes to output the significant wave height, the following line should be included in the case file: `VARIABLES FOR 2D GRAPHIC PRINTOUTS = HM0`. The complete list of available 2D output variables and information about how to specify them in the case file is available in the TOMAWAC user manual. The 2D variables are output in the TELEMAC Selafin binary file format that can either be read into MATLAB using a toolbox (the TELEMAC Tools toolbox is available on the Matlab Central File Exchange website), or read into the BlueKenue open source software program. BlueKenue has a useful set of built in tools for the visualization of Selafin format variables. It is recommended that, at a minimum, the user output the significant wave height field in order to check the time step and duration parameters for their model run, as described in the methodology (see Section 2).

In addition to the 2D variables, it is also possible in TOMAWAC to output the full directional frequency spectrum at any point in the domain, for up to 99 points in each model run. The (x,y) position of the desired points can be entered into the model run case file. For example, if the user would like to output the wave spectrum at the point (100 metres, 100 metres), the following two lines should be added to the case file:

```
ABSCISSAE OF SPECTRUM PRINTOUT POINTS = 100.00
ORDINATES OF SPECTRUM PRINTOUT POINTS = 100.00
```

The resulting file is a TELEMAC Selafin binary file that can be read into MATLAB using a toolbox. It is recommended that the user output the directional wave spectra at the locations of the WECs, as described in the methodology.

4.2 SpecWEC outputs

The output files generated by the wave energy device representations provided with SpecWEC were described in the previous section. There is one output file produced by the simple linear subroutine that contains the power absorbed by each WEC as a function of frequency. There are four output files produced by the point absorber routine, containing the power absorbed, power radiated, standard deviation of device displacement, and linearised PTO coefficient as a function of frequency for each device. These files are simple text files that can easily be read into any number of programs, including Matlab. In addition, if a new subroutine is written for another WEC (or an available subroutine modified) as specified in Section 3.2, then the author can add any number of additional output files that may describe the WECs’ responses.

4.3 Interpreting array outputs

The interpretation of SpecWEC results is dependent on the study objectives. The user needs to consider what they are trying to determine using the SpecWEC tool, prior to designing the experiment and running it. This will make it much easier to deal with the output. For example, the SpecWEC tool could be used to look at the impact on the shoreline that is down-wave of a wave farm. In this case, the user will want to make sure to output the significant wave height as well as the full directional wave spectra at key points in the domain. The user will probably also want to do two model runs, with and without the wave farm, for comparison.

It is almost certain that the user will wish to use the SpecWEC tool to estimate the annual average energy production of a wave farm. There two fundamentally different methods by which the annual average energy production can be calculated.

The first method is to use a time-series of the full wave spectra for a number of years and to take the average of the array power capture produced using this time-series. Assuming that the average is based on 10 years of wave data with a resolution of 3 hours[3] then this would require approximately 30,000 simulations. Whilst this may be possible at the final stages of design it is unlikely to be practicable for the assessment of multiple alternative layouts.

The second method is to use a parameterised representation of the wave climate so that it can be represented using a limited number of sea-states. Each of these sea-states would make a weighted contribution to the annual average energy production based on the number of actual sea-states that it represents. Unfortunately, there is no universal set of standard parameters that can used to parameterise the wave climate since they will not only depend on the characteristics of the wave climate itself, but also the characteristics of the wave energy converter and proposed wave farm. To identify a set of suitable parameters it is suggested that sensitivity analyses are used to determine which parameters have the most dominant impact on the power capture and thus should be used for parameterising the wave climate. It is likely that the sensitivity of the wave farm will be closely related to the sensitivity of an isolated WEC and so it is suggested that the initial set of parameters is based on those derived for a single WEC (it is assumed that by the time a wave farm for a particular WEC is being designed using SpecWEC that the characteristics of a single WEC, and thus how the wave climate should be parameterised, will be well understood). Additional parameters that may be particularly significant for an array of the WECs include the directional characteristics of the wave climate and the existence of marine currents; however, this does not preclude the requirement to assess the additional impact that aspects such as the spectral shape may have on the array performance before defining a set of parameterised sea-states.

An example of the use of SpecWEC for assessment of a wave farm is provided in WG1 WP2 D6/7 (PerAWaT 2013).

5 *Applications and limitations of SpecWEC*

The SpecWEC tool is a modification of a spectral wave model to include a parameterized representation of wave energy converters. The phase-dependent interaction of the wave energy converters and the flow field are not resolved in SpecWEC, which allows for a large saving in computational time. Moreover, it has also been shown that except for small closely packed arrays a phase-averaged representation of array interactions is generally adequate (Folley and Whittaker 2011). This means that SpecWEC can be used to model arrays of hundreds of wave energy devices in a relatively short time, compared to other existing numerical models. The phase-averaging means that the SpecWEC model may not reproduce the power capture of individual WECs in an array

---

[3] This number of years and resolution is recommended for modelling the wave resource by the project team developing the IEC Technical Specification on the wave resource (Folley et. al. 2012)

exactly and cannot give the time-series of the WEC response. However, it is expected that the model will be able to provide useful information to the user about the total power production of an array and how this may vary with array layout etc. Indeed, the comparison of SpecWEC with other numerical models (including WAMIT) and wave tank experimental data in WG1 WP2 D4 and D5 has demonstrated the accuracy of the SpecWEC tool. Averaging over all sea states and configurations, the agreement between total array power production for an array of heaving buoy point absorbers calculated by SpecWEC and the WAMIT model is better than 9%, and the agreement between total array power production calculated by SpecWEC and the wave tank data is better than 12%. These values indicate that SpecWEC has the potential be a useful tool for power production estimation, particularly when averaging over a large number of devices and sea states.

The current implementation of SpecWEC includes phase-averaged approximations of the energy absorbed and the energy radiated by the WEC. However, energy will also be re-distributed by diffraction from the WEC, which is currently not included within the SpecWEC model. The reason that diffraction is not currently included in the SpecWEC model is because there is not currently a suitable phase-averaged representation of diffraction due to a body that can be used. However, recent developments in modelling WECs have indicated that it should be possible to use the far-field asymptotic approximation of Kochin Functions to produce a phase-averaged representation of WEC diffraction. It would be expected that when this phase-averaged representation of WEC diffraction is included in SpecWEC that the accuracy of the model will be improved.

One of the fundamental limitations of SpecWEC is the inability to represent phase-dependent processes, such as constructive and destructive interference due to radiation and diffraction of waves around devices, whilst it is argued that as the separation distance between WECs increases the constructive and destruction interference patterns at different frequencies tend to cancel each other out so that a phase-averaged approximation becomes reasonable. However, the array layouts modeled in WG1 WP2 D4 and D5 were relatively closely spaced and the significance of phase-dependent interactions is evident when comparing SpecWEC to the WAMIT model on an individual device basis. The largest differences between SpecWEC and the WAMIT model are found in the centre of the array layouts, and this is probably due to the phase-dependent diffraction and radiation as calculated by WAMIT being more significant in the centre of the array. However, the idealized hydrodynamics as represented by WAMIT are not always fully representative of physical scenarios and may highlight issues that are not as significant as they may at first appear. This can be seen in the comparison of SpecWEC with the wave tank model results, which do not exhibit the same pattern of differences across the array and the largest differences are not focused in the middle of the arrays. Similarly, the performance of WECs in actual wave farms may also be affected by factors such as individual WEC variations, local marine currents, variations in water depth, etc. so that the apparent significance of phase-dependent interactions as predicted by linear potential flow models may be misleading.

Another current limitation of the SpecWEC model is the area method that is used to determine the source term strength from the power calculations. Although accurate, the calculation of the representative area of every WEC location is time consuming for large arrays of devices. However, based on initial investigations, the calculation of the correct area simply from mesh parameters is not straightforward. It seems likely that this area is dependent on the method of characteristics that is used to solve for the propagation of the waves in TOMAWAC. Collaboration with the development team of TOMAWAC, under the auspices of the SuperGen Centre for Marine Energy Research, is ongoing in an attempt to resolve this issue so that the representative area can be explicitly defined; however, significant progress may depend on the availability of further funding or resources. Unfortunately, to date (June 2013) an accurate method for automatically calculating the representative area has not been found; however, it remains a live issue for the development team.

The area method issue could potentially be resolved by implementing the subgrid scale representation of a wave energy converter in a different spectral wave model, namely SWAN. SWAN is very similar to TOMAWAC in that it solves the same wave action conservation equation, and includes physical mechanisms using a source term sink/strength representation. However, the algorithm used to solve the wave action conservation equation is different, as SWAN uses a simple finite difference representation where TOMAWAC uses the method of characteristics. Because the finite difference scheme solves over a clearly defined x and y space, it is possible that the area required for the source term strength may be more easily defined using this algorithm.

In conclusion, the SpecWEC concept is generally valid, as demonstrated in the results of WG1 WP2 D4 and D5, and can currently produce reasonable estimates of wave farm performance. However, there are a number of areas in which SpecWEC can be improved, both in the representative of the WECs (by inclusion of body diffraction) and in the implementation of the WEC source term in TOMAWAC. SpecWEC may not capture all of the detailed hydrodynamic interactions when the WECs are close-packed, but for actual wave farms this is not likely to be significant.

6 References

Canadian Hydraulics Centre (2010). Blue Kenue Reference Manual.

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Folley, M., Cornett, A., Holmes, B., Lenee-Bluhm, P. and Liria, P. (2012). Standardising resource assessment for wave energy converters. 4th International Conference on Ocean Energy, Dublin, Ireland.

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WAMIT. (2011). "WAMIT, Inc. - The state of the art in wave interaction analysis." http://www.wamit.com.

Appendix A: Shell script

```
      !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
      ! shellsource.f90 is the shell for the dynamic link library which contains the         !
      ! WEC source term calculation for SpecWec.  This subroutine should be made into a      !
      ! dynamic link library at compilation time.                                            !
      ! Written 18/05/2011 by Katie Silverthorne.                                            !
      !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

      subroutine WECSOURCE (TSTOT, TSDER, F, X, Y, NPOIN, NPLAN, NF, VENTX, VENTY, DEPTH, LT,
FREQ, TETA, DTSI)

      !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
      !  The following list describes the arguments of the subroutine:                       !
      !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
      !  NPOIN: integer containing the number of computational grid points                   !
      !  NPLAN: integer containing the number of directions                                  !
      !  NF: integer containing the number of frequencies                                    !
      !  LT: integer containing the time index of the TOMAWAC computation                    !
      !  TSTOT(NPOIN,NPLAN,NF): real array containing the total source term strength         !
      !                        (in m^2/rad)                                                  !
      !  TSDER(NPOIN,NPLAN,NF): real array containing the partial source term strength       !
      !                        (in m^2/rad) (For more clarification regarding the difference!
      !                        between the TSTOT and TSDER variables, please consult the     !
      !                        TOMAWAC user manual section 6.3)                              !
      !  F(NPOIN,NPLAN,NF): real array containing the directional spectrum of sea state      !
      !                     variance (in m^2/(Hzrad)                                         !
      !  X(NPOIN): real array containing the x coordinates of the computational grid points !
      !            (in metres)                                                               !
      !  Y(NPOIN): real array containing the y coordinates of the computational grid points !
      !            (in metres)                                                               !
      !  VENTX(NPOIN): real array containing the east/west component of the wind             !
      !  VENTY(NPOIN): real array containing the north/south component of the wind           !
      !  DEPTH(NPOIN): real array containing the water depth (in metres)                     !
      !  FREQ(NF): real array containing the computational frequency (in Hz)                 !
      !  TETA(NPLAN): real array containing the computational directions (in radians with 0 !
      !               radians corresponding to north and pi/2 radians to east                !
      !  DTSI: Real containing the source term integration time step                         !
      !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

      !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
      ! This section contains code which will expose subroutine WECSOURCE to the TOMAWAC     !
      ! main program and should NOT be modified by the user.                                 !
      !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

      !DEC$ ATTRIBUTES DLLEXPORT::WECSOURCE

      !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
      ! This section contains the variable declarations for the variables which are          !
      ! hardwired into the WECSOURCE subroutine and should NOT be modified by the user.      !
      !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
      !
      ! Number of computational points, directions, frequencies, and the time index
      INTEGER NPOIN, NPLAN, NF, LT
      ! Total and Part source term strength:
      DOUBLE PRECISION TSDER(NPOIN,NPLAN,NF),TSTOT(NPOIN,NPLAN,NF)
      ! Directional Spectrum:
      DOUBLE PRECISION F(NPOIN,NPLAN,NF)
      ! X and Y Coordinates of the computational grid
      DOUBLE PRECISION X(NPOIN), Y(NPOIN)
      ! East/west and north/south components of the wind field
      DOUBLE PRECISION VENTX(NPOIN), VENTY(NPOIN)
      ! Water depth
      DOUBLE PRECISION DEPTH(NPOIN)
      ! Computation frequencies and directions
      DOUBLE PRECISION FREQ(NF), TETA(NPLAN)
      ! Source term integration time step
      DOUBLE PRECISION DTSI
```

```
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
! This section is intended for the user to make any additional variable declarations, !
! and then include the source term calculation.  This section must contain statements !
! which set the total source term strength (TSTOT) and the source term strength with  !
! respect to the spectral energy density (TSDER).  If TOT is a variable which         !
! represents the total WEC source term strength, and DER is a variable which contains !
! the partial WEC source term strength, then the statement should be as follows:      !
!                   TSTOT = TSTOT + TOT; TSDER = TSDER + DER.                         !
! Note that the current value of TSTOT and TSDER must be added to, and not completely !
! rewritten.                                                                          !
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

RETURN
end subroutine WECSOURCE
```

Appendix B: Sample wecinfo.txt file for point absorber subroutine

```
!----------------------------------------------------------------
! Number of WECs
        10
!----------------------------------------------------------------
! Location format indicator (1 for nodes, 2 for x,y coordinates)
        1
!----------------------------------------------------------------
! Hydrostatic Stiffness
       3080000
!----------------------------------------------------------------
! Body Mass
        5400000
!----------------------------------------------------------------
! Number of output variables
        26
!----------------------------------------------------------------
! Number of heterogeneous input WEC parameters (device-specific)
        1
!----------------------------------------------------------------
! Node number/ x-y coordinates
        2223
        2227
        2231
        2235
        2239
        2243
        2247
        2251
        2255
        2259
!-------------------------------------------------------------------
! Added mass, radiation, and exciting force
  1539390.00  120764.505498  2724950.299540
  1501781.00  132808.681559  2649829.399210
  1462784.00  145785.063421  2559621.948520
  1422020.00  159604.749028  2451728.204555
  1379096.00  174024.581584  2323519.004450
  1333531.00  188556.825062  2172452.464525
  1285013.00  202252.260763  1996726.122510
  1233708.00  213406.457004  1796266.428530
  1180985.00  219267.095530  1573696.661460
  1130517.00  216059.470785  1335638.271380
  1089055.00  200243.956277  1093543.464160
  1064162.00  171081.309132  859880.316543
  1060023.00  132566.086776  646379.739393
  1074443.00  91932.832832   461328.548093
  1100534.00  56254.907914   309891.905197
  1130384.00  29832.845226   193907.380783
  1157839.00  13447.383017   111906.330946
  1180006.00  5004.043298    58650.759141
  1196431.00  1500.167718    27576.868586
  1208289.00  348.765789     11433.592848
  1216901.00  60.354610      4088.108973
  1223353.00  7.306298       1222.769614
  1228275.00  0.408367       300.721413
  1232138.00  0.028768       55.328266
  1235177.00  0.0            5.819498
  1237601.00  0.0            2.735691
!--------------------------------------------------------------------
! Heterogeneous parameters (damping coefficient)
     7000000
     7000000
```

```
     7000000
     7000000
     7000000
     7000000
     7000000
     7000000
     7000000
     7000000
!------------------------------------------------------------------
! Damping flag
     2
!------------------------------------------------------------------
! Area over which the energy is taken out
     630
     630
     630
     630
     630
     630
     630
     630
     630
     630
!------------------------------------------------------------------
! Upstream nodes
     2042
     2046
     2050
     2054
     2058
     2062
     2066
     2070
     2074
     2078
```