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Preface

This report covers a preliminary assessment of available numerical tools to be used in upcoming full dynamic analysis of the mooring systems assessed in the project "Mooring Solutions for Large Wave Energy Converters". The assessments tends to cover potential candidate software and subsequently cover their capabilities. The result of the assessments should make it possible to choose relevant software that will be used throughout the project and also in general use for mooring design of WECs.

The report is a part of *Work Package 1*: *"Task 1.2: Assessment of Available Numerical Tools for Dynamic Mooring Analysis"* and *"Milestone 1: Acquisition of Selected Numerical Tools"* of the project and was produced by Aalborg University in cooperation with Chalmers University of Technology.

Aalborg University, March 9, 2017

Contents

1 Introduction

Many different software tools for mooring analysis exists today, each with a set of specifications and a field of application. Most of the commercial software are aimed primarily at the offshore Oil & Gas and naval industry, with the capabilities of the software originally targeted at these. Wave Energy Converters (WECs) are employed at high-energy locations and are expected to experience a response different from that of e.g. Oil & Gas platforms. The applicability of the existing software for the wave energy sector is therefore not certain at present, as the capability to describe the conditions relevant for WEC mooring systems is decisive. This forms the basis of this assessment, which tends to clarify the specification of a range of relevant software packages, thereby providing a basis for choosing a suited tool for dynamic mooring analysis. The assessment tends not to compare analysis results but merely present the relevant software specifications.

1.1 Objectives of Present Mooring Analysis

In order to chose appropriate software, the software specifications needs to be evaluated according to the objectives of the present analysis. In the current research the mooring systems for four large, floating WECs will be designed and evaluated. These devices are all characterised by having a mooring system which is not an active part of the wave energy absorption and all are planned for deployment in shallow water depths.

The offshore Oil & Gas and naval sector has a tradition of designing the mooring system through quasi-static analysis, justified by the low responsiveness of the large masses and corresponding low velocities. In operational conditions, this might also be sufficient for WECs.

The design standards as e.g. API-RP-2SK [API, 2005] , ISO [ISO, 2013], IEC [IEC, 2014] and DNV [DNV-GL, 2010] states that the mooring system must be evaluated in an ultimate limit state (ULS), in which extreme wave, wind and current events are present. Here, a more dynamic behaviour must be expected for the WECs and the design standards states that a dynamic analysis for the final design must be performed.

Based on this and the fact that the ULS in general is determining for the overall cost of the WECs Zanuttigh et al. [2012], the main objective for the present study will be the dynamics of mooring lines in extreme conditions.

1.2 Area of Assessment

Based on the objective of the study, a range of parameters seems relevant to investigate and consider when choosing software package.

Time or frequency domain: Existing software differs between analysing in the frequency or time domain. Use of these different methods implies different advantages, as

analysis in the frequency domain often leads to faster calculations while analysis in the time domain in most cases are more time consuming. However, in the frequency domain the non-linearities of the system needs to be linearised, which is not necessary in the time domain. In a mooring system, significant non-linearities are present, and this needs to be considered.

De-coupled or coupled analysis: For some software the mooring analysis is performed as a de-coupled analysis, meaning that a separate analysis of the floating body motion is carried out initially and with the mooring system simulated as an added stiffness. The motions are subsequently applied to the connection points of the mooring lines and the dynamic cable analysis is carried out.

In a coupled analysis all interactions between mooring lines and the floating body are modelled directly and simultaneously. A coupled analysis is therefore also considered to be more sophisticated.

Floating body analysis: Some software packages are capable of modelling the floating body and calculate both motions and loads from environmental exposures. Many software packages need hydrodynamic coefficients as input in order to do this, while others has the option of performing a hydrodynamic analysis itself. The methods used are relevant to consider and compare.

Compatibility with other software: The possibility of direct implementation of input etc. from other software can highly benefit the analysis process. Especially in the case of de-coupled analysis, compatibility with other software is useful. However, in many cases a self-developed script can be used.

Implemented wave theories: Different wave theories can be applied when modelling waves. Le Méhauté [1969] described the area of application for different wave theories dependent on wave characteristics, cf. Fig. 1.1. Design standards as e.g. DNV-RP-C205 defines the same areas of application, which must be used when determining what theories that should be implemented in the software packages.

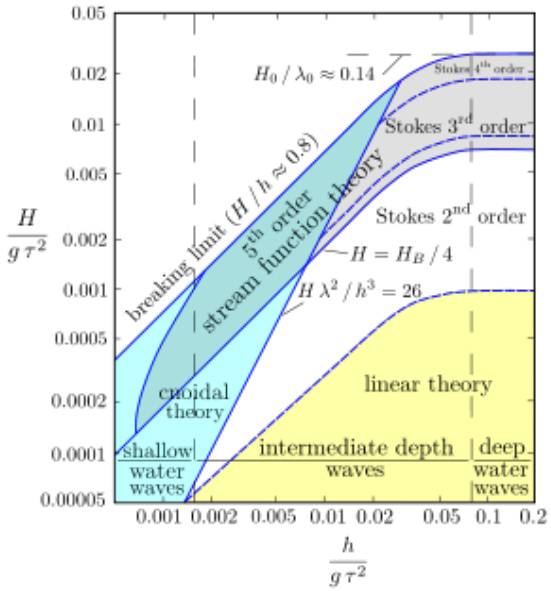

Figure 1.1. Application area for different wave theories dependent on wave height H, wave period T and water depth h, Le Méhauté [1969]

For the present study, where the devices are deployed in shallow to intermediate water depths, advanced theories as the stream function theory needs to be applied, cf. Fig. 1.1.

Also, implementation of relevant wave spectra can be beneficial.

Line theory: Different methods for modelling of mooring lines have been suggested, covering e.g. the Finite Element, Finite Difference or the Lumped Mass methods. Additionally, implementation of a small strain approximation, which is often seen in relevant software packages, can influence the analysis results, as this approximation is efficient in analysis of stiff materials such as chains or steel wire rope, but might not be suitable in analysis of materials like synthetic ropes.

Wind and current theory: The design standards have different demands to wind and current, including both how to model them and how to calculate induced loads. The specifications of the software need to correspond to the requirements from the standards.

Interaction with seabed: The methods for modelling the seabed can be different for each software, and the modelling of contact between lines and seabed therefore vary. Implementation of e.g. soil models might not be the same and therefore also result in different levels of detail.

Implementation of standards: Some software are developed or distributed by companies that produce the design standards, hence the software have them implemented. Others have also chosen to implement the standards and e.g. provide code check. This benefits the program, but might not necessarily be a demand. It is highly relevant to investigate the certification of the software packages to ensure that the finalized design are capable of being certified.

The parameters described above will be investigated and described for each relevant software and provide an overall outline of each software. This will then form a basis for choice

of model to use in assessment of mooring design for WECs.

1.3 Candidate Software

A large amount of mooring software exists, especially aimed at ports together with the naval, Oil & Gas industry. Many of these software are for quasi-static analysis, and therefore not considered in this analysis. Through an initial study the following list of candidates were found relevant for further investigation:

1. *Aqwa* by ANSYS Inc. [ANSYS Inc., 2013]
2. *Flexcom* by Wood Group Kenny [MCS Kenny, 2014]
3. *GMOOR32* by Global Maritime [Global Maritime Consultancy Ltd., 2007]
4. *MooDy* by Chalmers University of Technology [Palm and Eskilsson, 2014]
5. *MOSES* by Bentley [Bentley Systems, 2015]
6. *Orcaflex* by Orcina Ltd. [Orcina Ltd., 2013]
7. *ProteusDS* by Dynamic System Analysis Ltd. [Global Maritime Consultancy Ltd., 2015]
8. *SeaFEM* by Compass [Compass, 2014]
9. *Sesam DeepC* by DNV-GL and MARINTEK [DNV, 2005]
10. *WHOI Cable* by Woods Hole Oceanographic Institution [Gobat and Grosenbaugh, 2000]

The list of candidates covers software relevant and available for this project. However, many others exists, i.a. the in-house software *CASH* by GVA or *ZenMoor* by Zentech Inc. DHI Group has developed *WAMSIM* and are currently developing a new software expected to be released in summer 2015. *DeepLines Wind* by Principia & Energies Nouvelle also seems to be a relevant candidate for mooring analysis, but will not be released until mid 2015. Finally, a widely used software is the *Ariane-3Dynamics* by Bureau Veritas. For advanced cable analysis the software uses a cable-module based on *Flexcom* and developed by Wood Group Kenny. For that reason, it is not included in this assessment since *Flexcom* will be investigated.

2 Candidate Software

2.1 *Aqwa*

Aqwa, developed by ANSYS Inc., is a software package used in investigation of the influence of environmental loads from waves, wind and currents on fixed and floating offshore structures. The software is therefore considered a potential candidate for use in analysis and design of WECs and the applied mooring system. The software benefits from having a graphical user interface making both 2D and 3D graphic available. The software is available in different packages in which a cable dynamic package is available.

The analysis can be performed in both the time domain with all non-linearities included and in the frequency domain where non-linearities need to be linearised. Dependent on the applied calculation procedure the analysis can either be fully coupled or de-coupled.

Aqwa is equipped with a module capable of modelling the motion of the floating body, hence no input is required. *Aqwa* models the motions of the body from hydrodynamic loads covering drag, wave exciting and inertia loads. In case of large bodies compared to the incoming waves, the loads are determined by a three-dimensional panel methods, by use of fluid potential theory. Both 1st and 2nd order wave loads are calculated. 1st order effects on the body are solved by response amplitude operators (RAOs) and the 2nd order effects by quadratic transfer functions (QTFs). For slender bodies, *Aqwa* uses the Morison Equation approach.

The response of the system is calculated from the specified wave, wind and current conditions. *Aqwa* has different possibilities in modelling these.

Waves can be applied as either regular or irregular waves. Regular waves can be modelled as linear Airy waves or 2nd order Stokes waves. Irregular waves are modelled by superposition of the regular waves, and spectra such as JONSWAP, Pierson-Moskowitz, Gaussian or a user-specified spectrum are available. Time histories of wave elevations can be imported and used in analysis. Spread seas are also handled by Aqwa.

The wind is modelled as a mean wind combined with time varying gust effects. A wind profile describing the wind speed variation with height can be applied, together with different standard spectra such as the API, Ochi & Shing, NPD, ISO or a user-specified. Uniform wind or time histories of wind speed amplitude and direction can also be simulated.

The current can be modelled as either uniform or profiled with depth, but time variations of the current cannot be included. Interactions between the current and waves are modelled.

Loads from the current and wind on the floating body are calculated by a drag formulation, using a user-specified wind and current force coefficients, C_d, defined as $C_d = \frac{F}{u^2}$, where F is the force on the structure and u is the current or wind speed.

The seabed is modelled as a flat surface, which is additionally assumed horizontal in the dynamic cable solver. *Aqwa* models the seabed by springs and dampers, either

non-linear or linear if in frequency domain.

The Aqwa dynamic cable analysis includes tension and bending, but torsional deformation is not included. Further, it is based on the small strain approximations.

The dynamic mooring line is modelled using a discrete lumped mass approach, i.e. the line is divided into a number of segments where the mass of each element is concentrated into a corresponding node. The external forces are calculated using Morison's equations.

Aqwa uses an explicit two-stage predictor-corrector method for advancing in time, no further detail is found about the order or method.

2.2 *Flexcom*

Flexcom developed by MCS Kenny is a structural analysis software aimed at the offshore sector, and a potential candidate for mooring analysis. The software is used as the dynamic cable module in the *Ariane-3Dynamic* software package, which is used in offshore design and developed and distributed by Bureau Veritas. The software offers a 3D graphical user interface, in which models can be build and mesh generated automatically.

The software allows analysis in both the frequency and time domain, making it possible to perform a faster analysis in the frequency domain or a more detailed analysis in the time domain. In the frequency domain all non-linearities needs to be linearised, which is not necessary in the time domain. Both a coupled and de-coupled analysis can be performed dependent on the analysis procedure. *Flexcom* offers the possibility to perform code check with the DNV-OS-F101 (Submarine Pipeline Systems) and DNV-OS-F201 (Dynamic Risers).

When determining the motions of and loads on the floating body, user-input is necessary and the hydrodynamic analysis need to be done in an external software. *Flexcom* needs information on current and wind force coefficient, added mass and radiation damping coefficients together with RAOs and QTFs. The software is compatible with several software packages such as *WAMIT*, *Aqwa* and *MOSES*, from which these inputs can be directly imported. *Flexcom* computes the loads on the floating body and includes both 1st and 2nd order effects. First order effects are determined from RAOs and 2nd order effects from QTFs.

Flexcom models environmental loads from wave, wind and current, and offers a variety of different theories and possibilities. Both regular and irregular waves can be modelled with the irregular waves as a superposition of linear waves. Regular waves are modelled by either linear Airy waves, 5th order Stokes waves or Stream Function waves. Irregular waves can be simulated as different spectra covering JONSWAP, Pierson-Moskowitz, Ochi-Hubble, Torsethaugen and user-specified spectra. A time history of wave elevation can similarly be imported and simulated. *Flexcom* also offers the possibility to model spread sea states.

No information on definition of wind conditions is available in the theory manual of *Flexcom*, but it sates the wind load are included. Current can be modelled through different options. Generally, it is possible to model the current as either uniform or profiled with depth, but time variations are not included. The influence from the current on the waves are modelled as well. Loads from wind and current are calculated with a drag force formulation and user-specified force coefficients.

Flexcom allows defining a sea bed profile, defined either as flat, sloped or with an arbitrary bathymetry. The seabed is either modelled as rigid or elastic, where the latter either uses a linear spring or a non-linear force-embedment curve. Further, a seabed friction model is implemented. In case of a penetrating object, different layers with

different properties can be specified though P-y curves.

Flexcom solves for tension, bending and torsion, albeit it also have a special mooring line format that only includes tension in order to speed up computations. The model uses the small strain approximation in addition to assuming that the bending deformation is small.

The general finite element solution is based on a hybrid finite element beam model, where the axial displacement and rotation is given by a linear basis function, cubic basis function for the transverse displacements and constant basis functions for the extra variables axial force and torque moment. A Lagrangian constraint is then applied on the axial force and torque moment.

Time-stepping is done by second-order implicit generalised-α method with the option of a variable time step based on the current period parameter.

2.3 *Gmoor32*

GMOOR32 is developed by Global Maritime and is a quasi-static and dynamic analysis tool aimed at vessels in open sea. The software has a graphical user interface with 2D and 3D graphics. The software offers the possibility to perform code check with API-RP-2SK and DNV-OS-E301.

GMOOR32 is able to perform analysis in both the frequency and time domain, but can only do a de-coupled analysis. The motion RAOs are necessary input used by *GMOOR32* to calculate floating body motions. The motion of the fairlead is applied to the attachment point of the mooring cables, and the cable dynamics are analysed.

Since *GMOOR32* is not capable of doing the hydrodynamic analysis, a range of inputs is necessary. In order to calculate the motions of the floating body, RAOs need to be defined by the user, together with wind, current and wave force coefficient used in calculation of the environmental loads on the structure. The input needs to be produced in a format that requires other Global Maritime software.

GMOOR32 provides the option of simulating irregular waves modelled by superposition of regular, linear waves. JONSWAP and Pierson-Moskowitz spectra are the options provided by the software package. The possibility to model spread seas is available.

Wind can be modelled as a wind profile varying with height, and including wind spectra to account for the time varying gust effect. Different spectra including the API, NPD, Harris and Ochi & Shin spectra are available.

Current can be modelled as either uniform or profiled, with no option of time variations. The loads on the structure from both wind and current are calculated using a drag formulation using user-specified force coefficients.

The seabed is modelled as horizontal or sloped and includes friction effects. Non-linearities are included.

GMoor32 uses a discrete lumped mass approach. No further details are available in the user manual.

2.4 *MooDy*

MooDy is unlike the rest of the softwares described in this report not a complete software package, but only a dynamic cable solver. *MooDy* is therefore highly dependent on input and interaction with other scripts and codes. The code is developed by CHALMERS University of Technology initially in the Matlab code language but are at present undergoing development into a C++ version.

MooDy allows simulations in the time domain, and can be used in both a coupled an de-coupled analysis, dependent on the calculation procedure. Motion and loads on the floating body from environmental loads can not be assessed by MooDy and are a necessary input to the solver. *MooDy* has the ability to communicate with other software allowing the coupled analysis. For the latter a software or script calculating floater motions, communicate with *MooDy* throughout the analysis. The motion of the mooring point is calculated in each time step by the external software and read by *MooDy*, which then calculates the mooring force. This force is then send to the software which uses it in calculation of the mooring point position for the next time step.

As *MooDy* does not calculate motion, environmental load etc., no implementation of wind, current and wave models are present.

The sea bed is modelled by a linear spring and bilinear damper, and dynamic friction can be included.

MooDy only solves for the tension, but have no small strain assumption in the formulation.

A unique feature of *MooDy* is the use of spectral/*hp* discontinuous Galerkin method, i.e. an arbitrary order (set by the user) finite element method that allows discontinuities between the elements. The discontinuous solution is well suited for handling shock waves, such as snap loads, and comes to the cost of comes at the price of requiring more degrees of freedom per element. On the other hand, with a suitable choice of basis functions, the mass matrix becomes diagonal without resorting to the approximation of mass lumping. The use of high-order spatial resolution (pth order) gives that very few elements are required (for smooth solutions).

MooDy uses explicit time-stepping, including the third-order strong-stability-preserving Runge-Kutta scheme and a second-order leap-frog scheme.

2.5 *MOSES*

MOSES is a software package for modelling of offshore floating structures. The software is available in three different packages, each providing different capabilities. *MOSES* has a simple graphical user interface, where 3D graphics are available. Most commands are though in a scripting language. The software has a large range of applications and is capable of doing analysis of both stability, motion, mooring, structures and launching. The software is intended to be an overall software package used for the entire design and installation of the complete structure. *MOSES* performs code checking with AISC, API, NORSOK and ISO.

MOSES is capable of performing both frequency and time domain analysis, performed as either coupled or de-coupled. Further it is able to do a hydrodynamic analysis and thereby determine hydrodynamic coefficients and motion of the vessel. *MOSES* provides three different hydrodynamic theories for this, namely the Strip Theory, three-dimensional diffraction theory and Morison Equations. Calculations of motions and loads are based on the determined hydrodynamic coefficients for the specified floater.

Waves can be simulated as either regular or irregular waves. The regular waves can be either linear, Stokes 5th order or Stream theory waves. The irregular waves are superposed linear waves and JONSWAP and ISSC spectra are implemented. *MOSES* additionally has the ability to model spread seas.

Wind can be simulated as either vertically constant or profiled, following standards by ABS, API or NPD. Variations in time can be modelled as API, NPD, Harrus or Davenport spectra or a time history can be implemented.

Current is either modelled as uniform or profiled, and wave-current interaction can be included.

The loads from wind and current are calculated from a drag formulation, based on user-specified force coefficients.

MOSES models the seabed as combinations of springs and dampers, either linear or non-linear. Friction models can be defined and for penetrating objects, it is possible to define different properties for different layers in depth.

MOSES solves for tension, bending and torsion and solves the beam equations by linear finite elements.

MOSES use the implicit Newmark β-schemes, typically of second-order, for the time-stepping.

2.6 *OrcaFlex*

Orcaflex is a marine dynamic software package developed by Orcina Ltd. The software covers both static and dynamic analysis and are also aimed at design of mooring systems. *Orcaflex* has an extensive graphical user interface, and uses the graphic for set-up and analysis. The graphics allow both 2D and 3D views.

OrcaFlex primarily allows analysis in the time domain, and the analysis can be either coupled or de-coupled. Code check with API-RD-2RD, API-RD-1111, DNV-OS-F101, DNV-OS-F201 and PD 8010 are possible.

OrcaFlex models the motion of the floating body, based on output (displacement RAOs, Load RAOs, QTFs, Stiffness, Added Mass, Damping, Mass and Inertia) from an external radiation/diffraction analysis. *OrcaFlex* canot perform this analysis, and needs the data as input. However, OrcaFlex is directly compatible with software packages such as *Aqwa* and *WAMIT*, and can use the output from *MOSES*, *Ariane* and *WADAM* if small modifications are made.

Based on the input, *OrcaFlex* models both 1st and 2nd order effects, based on respectively RAOs and QTFs. In a de-coupled analysis *OrcaFlex* models motions from displacement RAOs and in the coupled analysis it models loads on the body from load RAOs, combine them with other external loads, and solves the motions from these. Additionally, *OrcaFlex* offers the option of using Morison's equations when determining loads. This is only applicable in cases where the size of the body compared to the incoming waves allows it.

OrcaFlex provides the possibility to simulate both regular and irregular wave states. The regular waves can be modelled as either linear, 5th order Stokes, Stream Function or Cnoidal waves. The irregular sea states are modelled by superposition of regular linear waves. JONSWAP, ISSC, Ochi-Hubble, Torsethaugen and Gaussian spectra are available, and spread sea can be defined.

OrcaFlex offers different possibility regarding modelling of wind and current. The wind profile can either be modelled as constant or varying with height above surface. API and DNV spectra together with input time history of wind speed and direction are available for simulation of variation in time.

Current can be modelled as constant with depth or with a non-linear profile. Magnitude and direction can be modelled as dependent on time. The load from wind and current are calculated from a drag force formulation with use of user-specified force coefficients.

The sea bed can be modelled as both horizontal, sloping or with a 3D bathymetry. Both linear and non-linear stiffness, in accordance with API standards, can be used when

modelling the sea bed and friction models are available. In case of penetration of the soil, API standard models for strength can be applied.

OrcaFlex solves for tension, bending and torsion using the small strain approximation for the axial tension.

The mooring dynamics equations are solved using a discrete lumped mass approach, with the segment mass concentrated at the end nodes of the segment. The segments are connected by axial and torsional springs and dampers.

Time-stepping can be either explicit by the first-order forward Euler method, or implicit by the second-order generalized α-method. It is worth mentioning that if the forward Euler method is chosen then several additional damping terms are added to the equations to stabilize the solutions, while for the implicit method *OrcaFlex* relies on the numerical dissipation of high-frequency noise that the α-method provides.

2.7 *ProteusDS*

ProteusDS, developed by Dynamic System Analysis Ltd., is a dynamic software for use in analysis of offshore structures, also aimed at mooring design. The software uses a full graphical user interface, and allows direct modelling of the system in the software.

ProteusDS has the ability to perform analysis in the time domain and primarily as a coupled analysis.

ProteusDS has the ability to model the loads on and motion of the floating bodies, through the Morison Equation approach. For cases where the Morison approach is not appropriate, ProteusDS needs the hydrodynamic properties from external software, covering added mass, damping, loading and RAOs as functions of wave frequency. Software as *WAMIT*, *MOSES* or *ShipMo3D* (by Dynamic System Analysis Ltd.) are directly compatible.

ProteusDS offers a variety of wave theories, and both regular and irregular waves can be modelled. The regular waves covers linear and 2nd and 5th order Stokes waves. Irregular waves are modelled as superposed regular and linear waves. Different spectra such as the JONSWAP, Pierson-Moskowitz and Bretschneider are available, and spread seas can similarly be modelled.

ProteusDS offers different possibility regarding modelling of wind and current. The wind profile can either be modelled as constant or varying with height above surface. Different build-in options for the profile are available. To model variation in time, *ProteusDS* have implemented the Ochi-Shin and NPD spectrum. Additionally time histories of speed and direction can be imported and simulated.

Similar possibilies are available for current as depth-varying profiles are available, but with a constant velocity throughout the entire simulation. Interaction between wave and current is neglected in *ProteusDS*.

When calculating wind and current loads on the floater, a drag force formulation is applied with use of user-specified drag coefficients.

The seabed can be modelled as both horizontal, sloping or with an imported 3D bathymetry. Both linear and non-linear stiffness of the seabed is possible and friction can be modelled.

ProteusDS solves for tension, bending and a quasi-static torsion using the small strain approximation for the axial tension.

ProteusDS uses a cubic spline finite element method, i.e. the solution inside an element is given by a fourth-order polynomial and the solution is actually C^2 continuous giving that not only the translations and moments also the first and second order derivatives

are continuous over element boundaries. In order to speed-up the computations the mass matrix is lumped. There is no discussion in the manual, if, and to what extent, this lumping affects the otherwise fourth-order spatial accuracy of the numerical solution.

The model is advanced in time using explicit Runge-Kutta schemes of fourth-order with adaptive time step. The numerical error introduced by the time integrator is maintained below user defined level by adjusting the time step.

2.8 *SeaFEM*

SeaFEM is a software package developed by Compass, with the aim of sea keeping and manoeuvring simulation with investigation of wave, wind and current effects on floating offshore structures. The software highly benefits from a 3D graphical user interface, with the possibility to generate models and mesh.

The software allows analysis in both frequency and time domain, and are capable of both coupled and de-coupled analysis. *SeaFEM* performs a hydrodynamic analysis itself, and therefore has implemented a second order diffraction-radiation analysis, for calculation of the hydrodynamic coefficients, using a time domain 3D Finite Element Method. Slender bodies are analysed by use of the Morison approach.

SeaFEM are capable of simulating linear, regular waves, together with irregular sea states defined by superposed linear waves. The JONSWAP and Pierson-Moskowitz spectra are both implemented together with the possibility to run user-specified spectra. Spread sea can additionally be simulated.

Definition of wind conditions with standard profiles and spectra are not implemented in *SeaFEM*, but wind forces can be applied as an external force on the body or as a local force. The wind load will therefore be constant.

Definition of the environmental conditions regarding the current is implemented and the current can be modelled with a constant velocity and direction. No application of profiles or time variations are supported. The load from the current is calculated from a user-specified force coefficient.

The seabed is modelled through linear springs and dampers. The friction between mooring lines and seabed can be modelled by a friction coefficient.

SeaFEM solves for axial tension, while neglecting bending and torsion.

The dynamic mooring equations are solved by linear bar elements and the solution is updated in time using an implicit second order Newmark scheme.

2.9 *Sesam DeepC*

Sesam DeepC developed by DNV-GL, is a software package consisting of the MARINTEK software *Riflex* and *Simo*, and is aimed at analysis of floating structures and mooring systems.

Sesam DeepC is capabale of analysing in both the frequency and time domain, and the analysis can both be fully coupled or de-coupled. *Riflex* and *Simo* are not capable of performing the hydrodynamic analysis, and therefore uses imported RAOs and QTFs to calculate loads and motions of the floating body. A software, *HydroD*, can be included in the *Sesam DeepC* package, and is capable of calculating the hydrodynamic coefficients or they can be directly imported from software as *WADAM* or *WAMIT*. *Sesam DeepC* calculates the 1st order wave frequency and high frequency motions and loads, and also includes the 2nd order low frequency effects.

For simulations, *Sesam DeepC* has implemented a range of wave theories for describing the waves. Regular waves can be modelled by linear wave theory or by Stokes 5th order theory. Irregular waves are superposed linear waves combined of both a wind sea and swell. A range of standard spectra are available including Pierson-Moskowitz, JONSWAP, Derbyshire-Scott, Ochi, Bretschneider and Torsethaugen. *Sesam DeepC* also includes the possibility to simulate spread sea states.

Wind can be simulated with a constant or time varying wind profile. Time series of wind velocities and directions can additionally be imported and simulated.

Similarly, current can be modelled as constant or varying dependent on time, both for speed and direction. The loads from wind and current are calculated from a drag force formulation with user-specified load coefficients.

The seabed is modelled by a vertical bilinear spring combined with a horizontal spring. Furthermore, inclusion of a friction model is a possibility.

Sesam DeepC uses the software *Riflex* which solves for tension, bending and torsion using small strain theory. *Riflex* comes with a linear bar elements and also with a hybrid beam elements using a combination of linear basis functions (for the horisontal displacements and torsion moment)and cubic basis functions (for vertical displacement and bending moments). The mass matrix may be lumped for more efficient computations.

Time integration is the implicit Newmark β-schemes of that are typically second-order (constant average acceleration scheme recommended) and solved with an Newton-Raphson method.

2.10 *WHOI Cable*

WHOI Cable is a software package aimed at mooring design, capable of doing both static and dynamic analysis. The software benefits from having a graphical user interface, but highly relies on a script language.

WHOI Cable is a time domain solver, capable of doing de-coupled analysis. The software to some extent has the ability to model the motions of and loads on the floating body, and different possibilities are available. One solution is to define the velocities of the floating body or alternatively the motions. Additionally, *WHOI Cable* is capable of calculating forces on the structure by the Morison approach. The calculated or defined motions of the floating body is used in the dynamic cable solver.

Waves are only described by linear waves, and can either be regular of random. No implemented spectra etc. are available but user-defined time dependent waves can be imported. The random seas are defined by the significant wave height and the wave peak period.

WHOI Cable can include wind effects in the calculation through a drag force formulation. Drag coefficients therefore need to be defined by the user. The wind can be described by a user-defined expression, giving the possibility of variations in time, and wind in two directions.

Currents are similarly defined as an expression, with the possibilty of time variations. Additionally variations with depth is possible, together with current in two directions. Loads from current are also defined by an user-specified drag coefficient.

WHOI Cable models the seabed by a linear spring and damper system. Implementation of friction though a static friction coefficient is possible. Sloping or horisontal seabed are both an opportunity.

WHOI cable solves the cable dynamics with tension, bending (based on Euler-Bernoulli beam theory) and torsion.The equations are solved by second-order central finite

differences in space together with second-order implicit generalised-α method in time and solved using an iterative method with relaxation.

3 Comparison of Candidate Software

Based on the area of assessment defined in Chapter 1 and the description of each software packages, the following section is used for comparison of the technical aspects of the software.

To a large extent, the software packages provides similar capabilities and since most codes are validated prior to publication, it is expected that the results obtained from use of the software packages will be in the same range. Some of the packages excel when comparing all specifications, and this will be discussed in the following text.

Considering Table 3.1 it is seen that all software packages are capable of performing time domain analysis, which is a requirement from the standards. Similar, most can perform coupled analysis except *GMOOR32* and *WHOI Cable*. This is considered a necessary feature.

Software	**Domain**		**Analysis**	
	Time	**Frequency**	**Coupled**	**De-coupled**
ANSYS Aqwa	✓	✓	✓	✓
Flexcom	✓	✓	✓	✓
GMOOR32	✓	✓	✗	✓
MooDy	✓	✗	✓	✓
MOSES	✓	✓	✓	✓
Orcaflex	✓	✗	✓	✓
ProteusDS	✓	✗	✓	✗
SeaFEM	✓	✓	✓	✓
Sesam DeepC	✓	✓	✓	✓
WHOI Cable	✓	✗	✗	✓

Table 3.1. Comparison of analysis method for software candidates. A blank cell means that no information was available.

As it was stated previously, design standards suggest use of wave theories dependent on the given site and conditions. For shallow water conditions, theories of higher order are required and the software needs to be able to model irregular sea states. It may not be considered a necessity that the software performs the hydrodynamic analysis itself, as it can get hydrodynamic coefficients as input. The table below can be used as comparison of implemented wave theories and floater motion analysis.

Most software are capable of simulating waves using higher order wave theories and all are capable of simulating irregular wave states. It is not relevant to consider *MooDy* in this table, as this code is only a mooring solver, and need additional code to simulate the hydrodynamics. Most sofware tools include second order effects. *ProteusDS* is in the considered release not capable of including the full contribution from 2nd order wave effects. Some wave drift is though included, and the full contribution will be included in future releases.

Software	Wave Theory						Hydrodynamic Analysis		
	Linear	Stokes	Stream	Cnoidal	Irreg.	Diff./Rad.	Morison	Input	2nd order
Ansys Aqwa	✓	2nd	✗	✗	✓	✓	✓		✓
Flexcom	✓	5th	✓	✗	✓	✗	✗	✓	✓
GMOOR32	✓	✗	✗	✗	✓	✗	✗	✓	
MooDy	✗	✗	✗	✗	✗	✗	✗	✓	
MOSES	✓	5th	✓	✗	✓	✓	✓		✓
Orcaflex	✓	5th	✓	✓	✓	✗	✓	✓	✓
ProteusDS	✓	5th	✗	✗	✓	✗	✓	✓	✗
SeaFEM	✓	✗	✗	✗	✓	✓	✓		✓
DeepC	✓	5th	✗	✗	✓	✗	✗	✓	✓
WHOI	✓	✗	✗	✗	✓	✗	✓	✓	

Table 3.2. Comparison of implemented wave theories and floater analysis. Blank cells means that no information was found.

Besides modelling the wave, the software needs to model the environmental loads from wind and current. Design standards states how to model these, and the table below compare the methods implemented in the software packages. Also the modelling of the seabed is compared.

Software	Wind			Current			Seabed		
	Uniform	Profile	Spectra	Uniform	Profile	Time	Linear	Non-linear	Friction
Ansys Aqwa	✓	✓	✓	✓	✓	✗	✓	✓	✗
Flexcom				✓	✓	✗	✓	✓	✓
GMOOR32	✓	✓	✓	✓	✓	✗	✓	✓	✓
MooDy	✗	✗	✗	✗	✗	✗	✓	✗	✓
MOSES	✓	✓	✓	✓	✓	✗	✓	✓	✓
Orcaflex	✓	✓	✓	✓	✓	✓	✓	✓	✓
ProteusDS	✓	✓	✓	✓	✓	✗	✓	✓	✓
SeaFEM	✗	✗	✗	✗	✗	✗	✓	✗	✓
Sesam DeepC	✓	✓	✓	✓	✓	✓	✓	✗	✓
WHOI Cable	✓	✗	✓	✓	✓	✓	✓	✗	✓

Finally the dynamic cable solver is compared and can be seen in the table below. Most software have similar capabilities, while *MooDy* and *ProteusDS* can be highlighted due to the high spatial and temporal order.

Software	Dynamic Cable Solver					
	Small Strain	Bending	Torsion	Spatial Order	Temporal Order	LM/FE/FD
Ansys Aqwa	✓	✓	✗			LM
Flexcom	✓	✓	✓	2nd	2nd	FE
GMOOR32						LM
MooDy	✗	✗	✗	pth	3rd	FE
MOSES		✓	✓	2nd	2nd	FE
Orcaflex	✓	✓	✓		2nd	LM
ProteusDS	✓	✓	✓	4th	4th	FE
SeaFEM		✗	✗	2nd	2nd	FE
Sesam DeepC	✓	✓	✓	2nd	2nd	FE
WHOI Cable	✗	✓	✓	2nd	2nd	FD

Considering the tables in the current chapter, is it clear that most software packages have similar features and all potentially can be used in analysis of WEC moorings, with *OrcaFlex*, *DeepC*, *SeaFEM* and *ProteusDS* considered to be the strongest candidates. ProteusDS has the most advanced cable solver, but since 2nd order wave effects cannot be included, it cannot be used at present.

It is worth to note that *SeaFEM* has the most advanced hydrodynamic solver, based on a FE formulation of the entire fluid domain. Frequency domain results (RAO and QTF) are therefore not needed and the software will provide a better description of non-linear waves. Potentially, the current effects will also be more advanced as they can be solved by integrating the pressure on the body, and not by a drag formulation with an estimated drag coefficient. This will though give much higher computational time, which might be undesirable for full analysis, where up to three hour simulations are performed.

DeepC and *OrcaFlex* both seems similar, with *DeepC* being slightly more advanced when considering the cable solver. Since both software packages have been validated and *OrcaFlex* is widely commercially used and *DeepC* is developed by the certification company DNV-GL, these two software seems like the strongest candidates.

In order to finally choose which software to use in full dynamic analysis, a benchmark study will be performed in later work.

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