LiftWEC

DEVELOPMENT OF A NEW CLASS OF WAVE ENERGY CONVERTER BASED ON HYDRODYNAMIC LIFT FORCES

Deliverable D3.1

Uncoupled Model of LiftWEC for preliminary concept assessment

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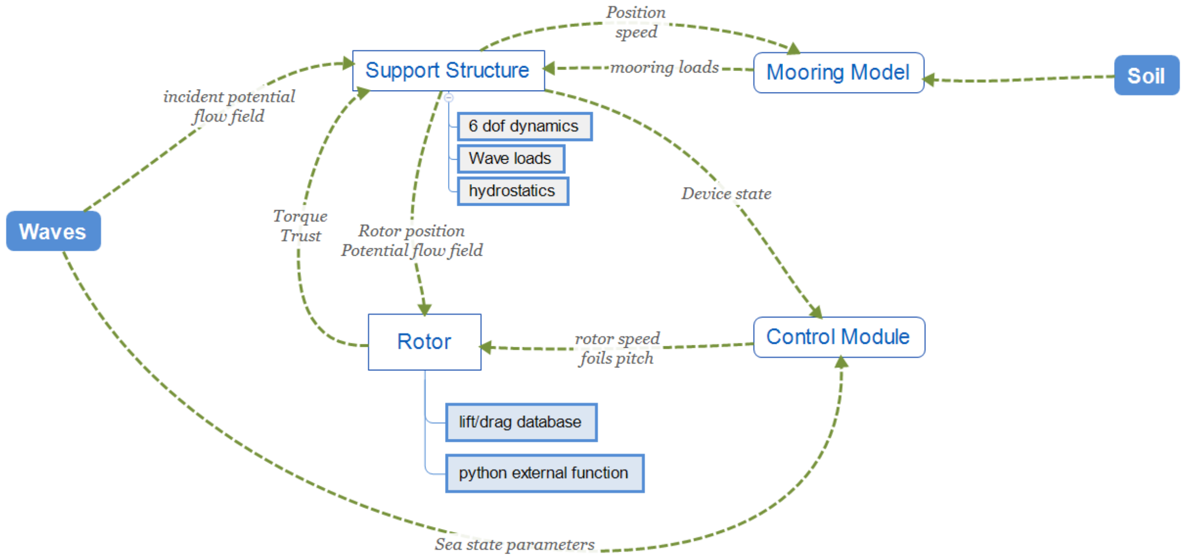
EXECUTIVE SUMMARY

The objective of this document is to present the architecture of the global model that is developed within the LiftWEC project to provide efficient simulation of the LiftWEC concepts. The global model provides a tool with coupled analysis of the rotor and support structure dynamic, and will be able to integrate advanced control strategies.

While the global model does not focuses on the precise hydrodynamic modelling of any elements of the LiftWEC concepts, it aims at providing an efficient and accurate enough modelling tool to provide inputs for design for the other work packages (physical modelling, structure, O&M, LCoE) and to support the assessment of the concepts.

From the tehnical specifications layed out in this document, the general architecture of the future global model is presented as a modular system. The data flow between the enviornment and the several computational module are explicited:



The support structure module will be based on linear potential flow hydrodynamics and the rotor module will implement a approach based on tabulated lift and drag coeficients of the foils. The flow velocity estimation at the hydrofoil levels considers the incident potential floaw and the radiated and difracted flow from the support structure.

A demonstrator model is presented. The comercial software Orcaflex is used to implement the support structure and the interaction with the rotor. A simple fixed speed control is considered. The rotor module is implemented by a external function that will form the core of the future rotor module. Lift and drag table coeficient are provided by LiftWEC partners.

The demonstrator module is used to simulate a possible LiftWEC configuration based on a slack-moored support structure and a 2 fixed pitch hydrofoils rotor. The results provided present the type of outputs that will be available from the future global model, i.e time series of speeds, rotor torque and trust, hydrofoils pahse angle and angle of attack of the foils among others.

NOMENCLATURE

Abbreviation	Signification
V_r [m.s^{-1}]	Rotation velocity of the rotor
T_s [s]	Wave period
u [m.s^{-1}]	Inflow velocity driven by the self-motion of the blade
v [m.s^{-1}]	Inflow velocity driven by the fluid particle motion of the water
w [m.s^{-1}]	Relative inflow velocity
F_L [N]	Lift force
C_L [-]	Lift coefficient
F_D [N]	Drag force
C_D [-]	Drag coefficient
S [m^2]	Foil surface
ϕ	Flow potential
P_r [m]	Rotor axis position
V_r [m.s^{-1}]	Rotor axis velocity
ω [rad.s^{-1}]	Rotor velocity of rotation
U [m.s^{-1}]	Velocity of the foil in the global coordinate system
β [rad]	Hydrofoil pitch
α [rad]	Angle of attack of the hydrofoil
τ_r [kN.m]	Rotor torque
T_r [kN]	Rotor trust
τ_g [kN.m]	Gyroscopic torque

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1 INTRODUCTION

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While the global model does not focuses on the precise hydrodynamic modelling of any elements of the LiftWEC concepts, it aims at providing an efficient and accurate enough modelling tool to provide inputs for design for the other work packages (physical modelling, structure, O&M, LCoE) and to support the assessment of the concepts.

This document summarizes the technical specification of the global model. It lays out the expected code architecture that will be develop and presents the functions and scientific background of the separate modules.

To support the development of the global model, a demonstrator code based on a commercial framework is implemented. Results from a case study are presented to demonstrate the functionalities and outputs of the future codes.

Finally, the future work to be conducted is presented.

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2 TECHNICAL SPECIFICATION

Prior to the start of coding and developing a numerical framework for the global model, an overview of the requirement for the code is generated. The requirement covers the following elements for each code:

1. Licensing
2. Users: who will use it and how
3. Expected theory and limitation
4. Desired functionalities
5. Inputs/outputs
6. Practical IT aspect

1.1 LICENSING

There is no requirement for the code to be used outside of the LiftWEC project, and therefore there is no requirement to consider the possibility to distribute the code.

The code however should be usable by the different partners of the LiftWEC consortium, and as such should not be restricted by the uses of commercial licenses not available to the different partners.

Finally, the code should be developed using libraries allowing a commercial usage of the produced results.

1.2 EXPECTED USERS

The model in its different versions should be usable by the different partners of the project. As such, the final versions of the numerical models should be provided in an environment that is usable & controllable. This uses of the code also constrains the licensing requirements to ensure that no commercial license is required by the different potential users.

The development and future maintenance of the code remains the responsibility of INNOSEA.

1.3 DESIRED FUNCTIONALITIES

The functionality of the global model codes should be the following:

1.3.1 Environmental modelling

1.3.1.1 Wave types

- Regular waves: the code should be able to model regular wave at a specific frequency, with a given period, amplitude and direction of propagation
- Unidirectional waves: the code should be able to model irregular unidirectional spectrum, specified from sea state parameters (Hs, Te, gamma, mean direction) or in matrix format detailing the amplitude and frequency of each components
- Multidirectional irregular waves: the code should be able model irregular multidirectional waves, specified from sea state parameters or in matrix format detailing the amplitude, frequency and direction of each components

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Inputs matrices could be defined in specific input files.

1.3.1.2 Current

Currents are not core to the development of LiftWEC concepts at this stage. However, the numerical framework should consider the possibility to evaluate the impact of simple current modelisation on the concept. Provisions for homogenous speed current should be accounted for.

1.3.1.3 Wind

Wind effects are not expected to be important for the development of LiftWEC, therefore there is no requirement to include wind modelling into the codes.

1.3.1.4 Bathymetry

Constant finite depth geometry should be considered and included in the wave and current modelling.

1.3.1.5 Data sources

The code should be able to use data from mainstream metOcean modelling tools and outputs for current EU collaborative project such as ResourceCode. Having the capability to integrate directly such source of data is valuable for the future usability of the code.

1.3.2 Wave generation

The wave modelling of irregular waves will use single summation, deterministic methods (see [1], [2])

1.3.3 Dynamic modelling

The code should be able to consider the different LiftWEC configurations and the dynamic of its main components. The following types must be considered:

- Freely floating WEC with one or multiple rotors connected to a support structure. The support structure can be slack-moored or taught-moored
- Fixed foundation WEC with one or multiple rotors connected to a support structure. In such case, the DoFs of the support structure must be constrained.

1.3.4 Control

The code should be capable to run using the control algorithms developed within WP5. This capability should consider the likely evolution of the control requirement in future developments of the project.

It is important to ensure that the numerical model for the LiftWEC project is suitable for control design. One of the main goals of the control WP5 is to maximise the performance function (PF), which will have a simple definition at the first stages of the project (see [3]). Initially the PF have to ensure maintaining an operational rotation speed and torque for the turbine/electricity generator for the different waves input. Subsequently, its requirements will be expanded and include minimisation of the operational expenditures, loads on actuators, fatigue analysis and etc. This function must be added to the program code and tracked during the modelling processes. It is also important to make this code flexible for modifications. It should be connected to the outer program function. The PF will evolve with the future development of the project and its WPs. Generally, it is planned to conduct two types of optimisations:

- Single-objective optimization for the Levelized Cost of Energy, which will be implemented for the fast models and real time control.

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- Multi-objective optimization or Pareto optimisation for the slow models and lifetime performance review.

The LiftWEC is controlled considering the following operating strategies:

- Phase-locked or phase-independent rotation
- Moment of inertia control
- Hydrofoil radius control
- Hydrofoil pitch control

In order to implement these strategies, the following parameters should be available for the real-time manipulations:

- Rotor radiuses
- Hydrofoils pitch angles
- The load torque on the WEC shaft
- The distance between the rotation centre and free surface

1.3.5 Computational functionality

Multicore processing allowing the parallel processing of several independent simulations should be considered. This should allow the efficient processing of batches of simulation launched from the command line interface (see section 1.5.1)

1.3.6 Simulation parameters variability

It is not expected that input parameters variability needs to be taken into account within the global numerical model. The environmental parameters and the device characteristics including the slow control elements (device characteristics that could potentially be modified on a timescale compatible with sea state per sea state basis such as ballasting) should be considered constant during a simulation.

1.4 INPUTS/OUTPUTS

1.4.1 Inputs

1.4.1.1 Simulation definition

The following parameters should be accessible and varied for different tests:

Table 1 - Simulation parameters inputs

Parameters	Unit	Comment
Duration	[sec]	The length of the simulation to be analysed
Ramp up	[sec]	Length of time to ramp up wave and current before the main body of simulation
Sampling frequency	[Hz]	Fix frequency at which results should be exported

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2.1.1.1 Wave parameters

The model should be able to model regular wave from the following inputs:

Table 2 - Regular wave parameters inputs

Parameters	Unit	Comment
Period	[s]	Period of the wave
Amplitude	[m]	Amplitude of the wave
Direction of propagation	[deg]	Direction of the wave in global frame, 0deg is the direction from positive X axis to negative X axis.

The code should be able to model irregular unidirectional or multidirectional waves spectrum, specified from:

Table 3 - Irregular wave parameters inputs

	Parameters	Unit	Comment
Option 1	Hs	[m]	Significant wave height
	Te	[s]	Energy period
	gamma		JONSWAP peak parameter
	Mean direction	[deg]	
	Directional spreading s		Directional spreading modeled with a $\cos^{2s}$ function
Option 2	Sea state	[-]	Matrix format detailing the amplitude and direction of each components

1.4.1.2 Device definition

The devices will be defined by the following elements:

Parameters	Unit	Comment
Mass properties of the bodies	[kg], [kg.m^2], [m]	Mass, mass moments of inertia and centre of mass of the bodies
Hydrodynamics characteristics of the foils	[-]	Lift and drag coefficients from the CFD analysis
Area of the hydrofoils	[m^2]	The area of the hydrofoil is used for the drag and lift calculation
Radius of the rotor	[m]	The radius of the rotor can be fixed or an output from a control module (see Table 4)
Chord of the hydrofoils	[m]	The chord of the hydrofoil is used for the Reynolds number calculation
Support structure hydrodynamic characteristics	[-]	Obtained from BEM (ex: WAMIT, NEMOH)

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Support structure hydrostatic characteristics	[-]	Obtained from BEM (ex: WAMIT, NEMOH)
Mooring stiffness	[kN/m]	Mooring stiffness applied to the support structure

The control design can induce constraints on the devices. Following the need of WP5, the model takes in inputs the parameters presented in Table 4.

Table 4 - Parameters of the control

Parameters	**Unit**	**Comment**
Shaft torque	[kN.m]	Additional torque applied to the rotor
Hydrofoil radius	[m]	Radius from the rotor axis to the hydrofoils
Hydrofoil pitch	[deg]	Orientation of the pitch relative to the device
Rotor depth	[m]	Depth of the rotor axis

1.4.2 Outputs

The global model should provide the following outputs:

Parameters	**Unit**	**Comment**
Position of hub and rotor	[m], [deg]	Position relative to global axes and rotation
Velocity of hub and rotor	[m.s^{-1}], [rad.s^{-1}]	The magnitude and components of the velocity and angular velocity
Acceleration of hub and rotor	[m.s^{-2}], [rad.s^{-2}]	The magnitude and components of the acceleration and angular acceleration
Applied moment and forces on the rotor	[kN], [kN.m]	Moment and forces resultant of the hydrofoils hydrodynamic
Reynolds number	[-]	Reynolds number on each foil, or foil section
Position of foils	[m]	Position of each foil in global and local system
Drag and lift forces	[kN]	Drag and lift forces magnitude and components in local frame
Inflow velocity (driven by rotation of the rotor)	[m.s^{-1}]	Inflow velocity (driven by the rotation of the rotor) magnitude and components in local frame
Fluid velocity at the hydrofoil position	[m.s^{-1}]	Fluid velocity magnitude and components in local frame, at the hydrofoil position

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Relative inflow velocity	[m.s^{-1}]	Relative inflow velocity magnitude and components in local frame, for each hydrofoil
Phase angle φ	[deg]	Phase angle between the fluid and the hydrofoil motion ϕ, for each hydrofoil
Attack angle β	[deg]	Attack angle β of the hydrofoils
Mooring loads	[kN]	Mooring load on structure
Loads at the hydrofoil supports	[kN]	Load on the support hydrofoils
Power production estimation	[kW]	Estimated as the product of the rotor speed and the rotor torque

1.5 PRACTICAL IT ASPECT

1.5.1 Interface

A command line interface is sufficient. There is no specific requirement for a Graphical User Interfaces.

1.5.2 IT requirement

The code should be usable on normal desktop PC equipment. Simulation time should be in the order of minutes/hours for an irregular sea states, not days.

3 THE GLOBAL MODEL DEFINITION

3.1 COORDINATE SYSTEMS

Three frames are defined:

- Global frame G: global frame of the system. The wave direction is along the negative axis Gx.
- Local frame L: local frame of the rotor connection. The Lx axis is oriented along the length of the rotor. The rotation of the rotor is negative on the axis Lx. On Orcaflex this frame corresponds to the local frame of the constraint between the rotor and the floater.
- Local frame LO: local frame of the rotor. This local frame has the same rotation that the rotor in Orcaflex. The external function used this frame to applied forces and moment.

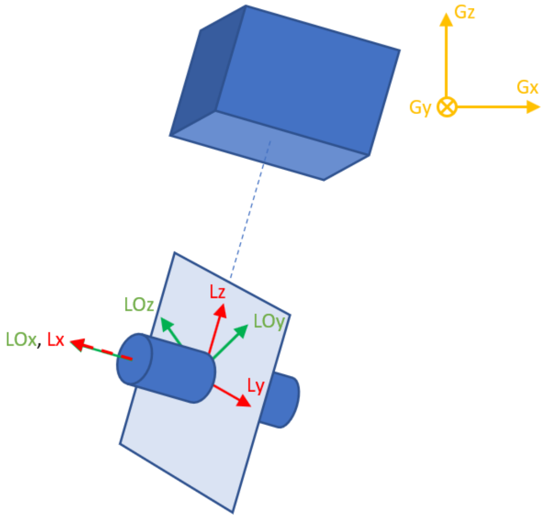

Figure 1 – Frames definition

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3.2 CODE ARCHITECTURE

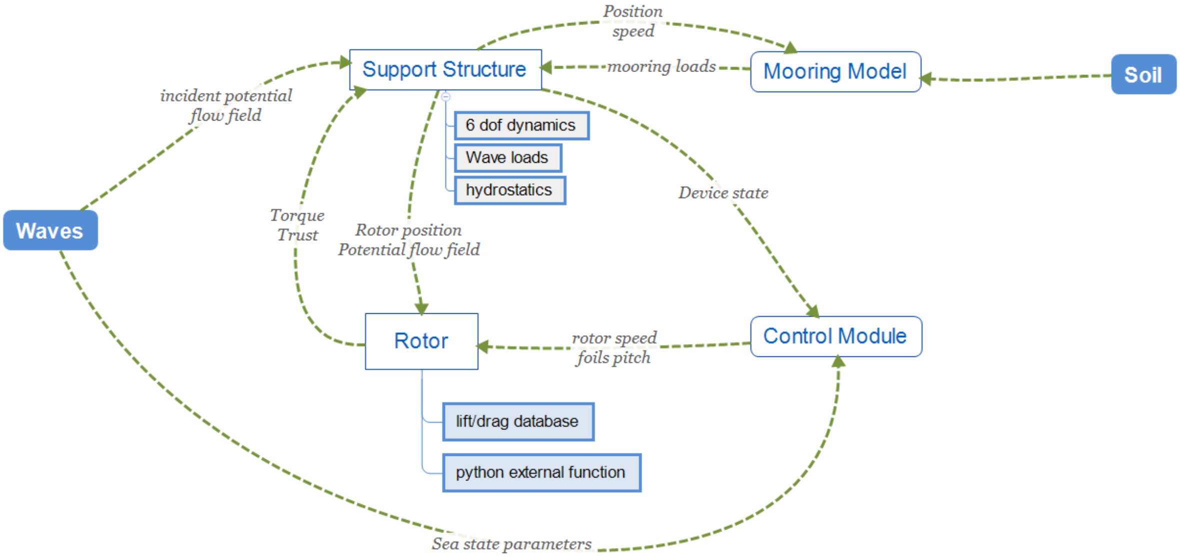

Figure 2: Architecture of the global model

Figure 2 shows the architecture of the global model. In the demonstator presented in this study, Orcaflex is used to model the support structure and to provide a mooring model. The development is focused on the external python function which models the lift and drag of the rotor. At this stage, the rotor velocity of rotation and the hydrofoil are fix during a sea states, but a future control module would be able to provide a time step by time step command of these elements.

3.3 ROTOR HYDRODYNAMIC

The rotor hydrodynamic module estimates the torque and thrust of the rotor. It also provides an estimation of the gyroscopic torque due to the rotor rotation.

Configurations with multiple rotors will be able to use multiple independent instances of the rotor module.

Inputs to the module:

- Flow potential $\phi(t)$, from the support structure dynamic module
- Rotor axis position P_r and speed V_r, from the support structure dynamic module
- Rotor velocity of rotation ω, from the control module
- Hydrofoil pitch, β, from the control module
- Hydrofoil hydrodynamic characteristics: tabulated lift C_L and drag C_D coefficients as a function of the angle of attack, α, and the Reynolds number.

Outputs of the module:

- Rotor torque τ_r
- Rotor thrust T_r
- The gyroscopic torque τ_g

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The lift F_L and drag F_D produced by the hydrofoils are determined using the hydrodynamics characteristics of the foils calculated by the high-fidelity model for a given range of angle of attack and Reynolds number.

Depending on the hydrofoil geometry and length, the hydrofoils are discretised longitudinally and the lift and drag is assessed independently on each hydrofoil section. *U* is the velocity of the foil in the global coordinate system, which contains the velocity of the foil driven by rotation *u* and the velocity of the rotor V_r from the support structure dynamic module.

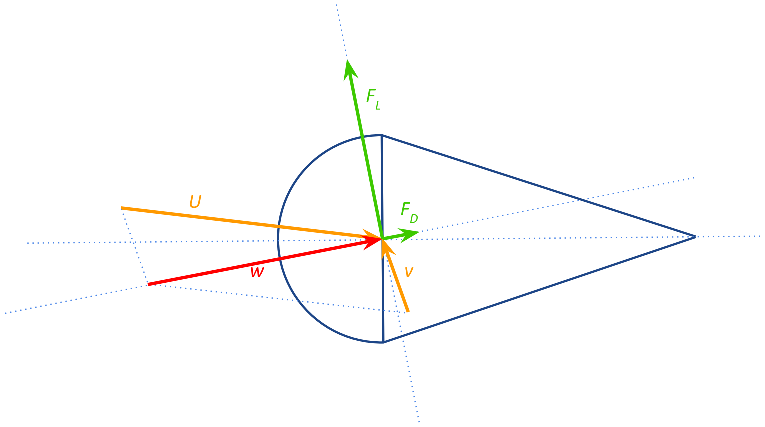

Figure 3 - Example simplified velocity and force components on a blade

At each time step, the relative inflow velocity *w* between the hydrofoil and the water is estimated as the resultant of the inflow velocity driven by the fluid particle motion of the water *v*, and the inflow velocity driven by the self-motion of the blade *u*. The hydrofoil pitch can be considered.

The fluid particle motion *v* is estimated from the flow potential $\phi = \phi_i + \phi_r + \phi_{ir}$, with ϕ_i the incident potential flow, ϕ_r the flow potential reflected by the support structure and ϕ_{ir} the flow potential radiated by the support struture (non-fixed devices). Some simplification might be possible depending on the configurations. Fixed devices supports on jack-up struts with thin section might not require the reflected and radiated flow potential. The estimation of ϕ is completed by the support structure model and passed as an input to the rotor module.

Once the relative inflow velocity *w* is estimated for each foil section, the lift and drag coeficients can be obtained from the tabulated database.Those coefficients depend on the Reynods number R_e and the attack angle of the hydrofoils β. The calculation of the Reynold number is done based on the characteristic's values of the hydrofoils:

$$R_e = \frac{wL_c}{\nu}$$

Where w is the relative inflow velocity *w* between the hydrofoil and the water, L_c is the chord length of the hydrofoil, and ν is the kinematic viscosity. The values of R_e and β in the tabulated database are interpolated to extract corresponding hydrodynamic coefficients.

The calculation of the lift and drag for each section is done following formulas:

$$F_L = \frac{1}{2}\rho w^2 S C_L$$

$$F_D = \frac{1}{2}\rho w^2 S C_D$$

where ρ is the density of the water, S is the area of the hydrofoil, C_L is the lift coefficient and C_D is the drag coefficient. The area of the foil is approached by the product of the hydrofoil chord and the length of the rotor axis.

Drag on the hydrofoils support and the axis support will considered separataly as rquired by the considered rotor onfiguration.

3.4 SUPPORT STRUCTURE DYNAMIC

LiftWEC concepts will present a range of solutions to support the rotor and provide a source of reaction torque. Some of the support structure might be freely floating, and therefore the global model should be able to simulate the 6 degree of Freedom of the support structure. For configurations were the rotor hub motions are constrained, the support structure module will have the possiblity to deactivate the unnecesary DoFs.

For fixed structure, the loads to be resisted by the foundations will be estimated.

3.4.1 General assumptions

The global model considers the support structure as a rigid body with 6 degree of freedom. Depending on the configurations, some of all the degrees of freedom might be limited.

The mass properties of the rigid body considered in the dynamic time domain equations includes the rotor inertia at rest.

3.4.2 Loads

The loads to be considered are:

- hydrostatics loads
- the wave loads on the structure
- the rotor loads on the structure
- the mooring loads, if applicable, on the structure.

The wave loads will be estimated by potential flow theory on the support structure, considering the incident wave potential only. The wave potential radiated by the rotor itself is neglected.

An industry accepted code such as Wamit or Nemoh will be used to compute the hydrodynamic coefficient (added mass, radiation damping, irf, excitation forces amplitudes and phases) and hydrostatic characteristics of the device (linear hydrostatics considered with hydrostatic matrix). In the first version of the global model, the hydrodynamic coefficient of the rotor is not considered. Further iterations of the software tool will consider a method to include. 1st order loads only are considered in the first version of the global model.

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The rotor loads are provided at each time step by the rotor module defined in section 3.3. The loads consist of the rotor thrust, torque in the axis of rotation and the gyroscopic torque.

A linear mooring model will be implemented using stiffness and damping matrices.

3.4.3 Dynamic solver

The dynamic equation of the support structure will be solved in time domain. The exact method used to estimate the convolution integral is yet to be defined. The initial solution will however be based on INNOSEA's experience and use the method implemented in InWave [4] [5].

3.5 DEMONSTRATOR (ORCAFLEX) MODEL

A demonstrator model is used at the early stages of the project, which principally allows the development of the rotor module. The support structure module is handled by an existing commercial code, Orcaflex, and the rotor module is handled by an external python function. A study case is presented in the following sections to demonstrate the functionality and outputs of the codes. The framework of the demonstrator code might be used to assess the initial LiftWEC concepts.

3.5.1 Orcaflex presentation

Orcaflex performs global static and dynamic analysis of a wide range of offshore systems, typically including boundary conditions such as vessels, buoys, etc., as well as finite element modelling of line structures. More information can be found at www.orcina.com/orcaflex/ , including:

- a list of applications
- a technical specification
- a demonstration version of Orcaflex
- a set of pre-run example files
- a set of validation cases

3.5.2 System

The system consists of 2 interconnected entities:

- the buoy, modelled in Orcaflex as a 6 degrees of freedom rigid body
- a phase locked rotor with 2 hydrofoils

The demonstator case considers a freely floating support structure but it can be easily changed to a fix support structure within the Orcaflex framework by constraining its DoFs.

The buoy is considered as a rigid body with 6 degrees of freedom: three translational and three rotational. The buoy is defined as a box of 6m height and 100m^3 volume. The mass of this body is set to 30te.

A mooring stiffness is added to the buoy, to limit is displacement during the simulation. The translational stiffness (along x, y, and z axis) is fixed to 20kN/m, and the rotational stiffness (along Rx, Ry and Rz) is set to 20kN.m/deg. These stiffnesses are applied at the centre of the buoy. Following the

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preliminary study done on LiftWEC [6], a first model is defined: two hydrofoils are considered in the system, and the initial phase deviation of both foils are respectively -90° and +90°. It is assumed the device rotates with the wave (i.e. in the same direction as the orbital particle fluid motion). The velocity of the rotor is fixed to allow the system to be in phase with the waves, considering the significant wave period T_s (wave period for regular waves, to be defined for irregular waves):

$$\omega_r = \frac{2\pi}{T_s}$$

The relative inflow velocity *w* is the resultant of the inflow velocity driven by the fluid particle motion of the water *v*, and the inflow velocity driven by the self-motion of the blade *U*. Two components are considered for the self-motion of the foils: the velocity *u* driven by the rotational velocity of the device ω, and the displacement of the floater and the rotor in the water V_r.

The axis of the rotor is modelled within Orcaflex as a lumped body (more information in [7]) connected to the buoy by a constraint of one degree of freedom along the Lx axis (see Figure 1). The moment of the foils is applied from an external function, on the local frame. The diameter of the rotor used to determine the position of the foils can be set directly on Orcaflex, in tags of the lumped body. The rotational velocity of the rotor is set in the external function, and it is considered constant.

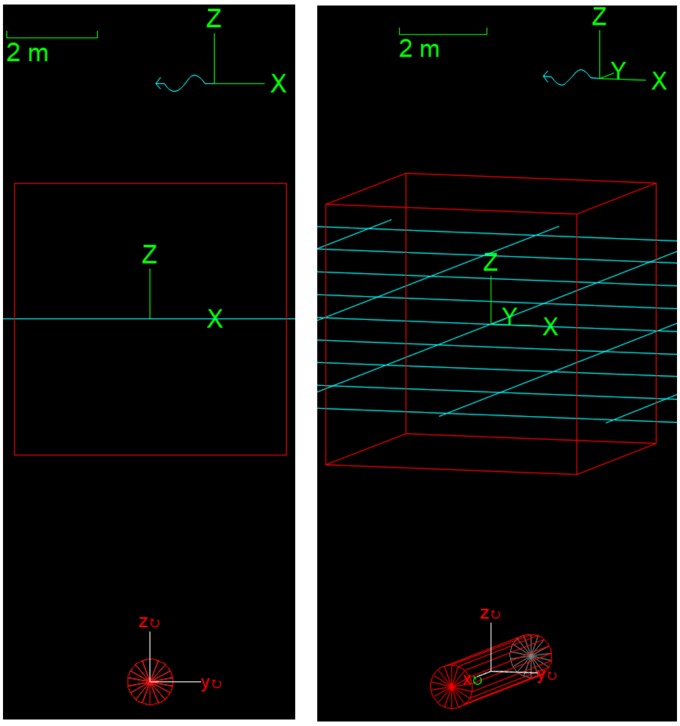

Figure 4 – System considered in Orcaflex

The Figure 4 shows in red the local axis of the rotor in the system, where the moment is applied. In the global model the waves come from the positive X axis. To be in the same direction that the waves the rotor is rotating in the positive sense of the local X axis.

3.5.3 External function

The external function is written in Python 3, using the Orcaflex API (for more information see [8]).

3.5.3.1 Hydrofoils consideration

At each time step, the position of the rotor, and the velocity of the water particles are obtained from Orcaflex. The positions of the foils are determined from the position of the rotor, the radius of the system and the rotor velocity.

Following the technical specification, for each foil, the relative inflow velocity is determined from the water velocity at its position and the inflow rotation velocity of the foil. The angle of attack is computed from this velocity.

The hydrodynamic coefficients are extracted from a csv file supplied by TUHH. A double interpolation and/or extrapolation is done on pitch angle of the foil and on Reynolds number to obtain the lift and drag coefficients. The associated forces are then calculated, following technical specification.

The associated moment is determined and applied to the axis of the rotor from Orcaflex. The resultant of hydrodynamic forces of each foil is also applied to the support structure modelled in Orcaflex.

3.5.3.2 Structure

The principal steps of the external function are resumed in the following table:

Initialization	• Gets the properties of the WEC (radius, foil area, foil chord) • Calculates the velocity of the rotor from the wave definition • Computes the initial position of the rotor • Reads and stores the list of drag and lift coefficient • Gets the environment properties (kinematic viscosity, water density)
At each step	• Gets the position of the rotor • Computes the position of the hydrofoil • Gets the water velocity at the foil position • Computes the relative inflow velocity for each blade • Calculates phases of the foils • Computes pitch attack angles of the blades • Determines for each foils Reynolds number • Calculates the drag and lift force • Applies the drag and lift forces and moment on the rotor
Outputs	• Position of foils • Relative velocity of foils • Relative fluid velocity (from waves) at foils positions • Relative inflow velocity at the foils • Lift and drag of the foils • Phase angle between the fluid velocity and the foils motion • Attack angle of the foils

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	• Reynolds number at foils

The outputs are displayed in Orcaflex, and they are computed at each time step. The user can select a specific period, and plot or get the values in a table. The outputs are handled via the Orcaflex API.

3.6 LIMITATIONS

In this first version of the model several simplifications are done:

- The wave loads on the support structure only considers the hydrodynamic properties of the support structure without the rotor. Elements such as the rotor added mass and radiation damping are not considered at present;
- No physical connection is considered between the rotor and the foil, and between the rotor and the floater;
- The weight of the foils is not considered;
- Effect of reflected and radiated waves on foils are not considered;
- The mooring is considered linear;
- The rotor velocity is fixed. The rotor dynamics are not considered.
- Drag on the hydrofoil supports and rotor axis are not considered in this early veriosn

4 STUDY CASE & RESULTS

4.1 PRESENTATION OF STUDY CASE

A study case is defined to demonstrate the functionalities of the demonstrator model.

Table 5 presents the rotor's parameters of the study case. Those properties are arbitrary and do not represent a valid system.

Table 5 - Properties of the study case

Depth of the rotor axis [m]	-8
Hydrofoil radius [m]	5
Rotor width [m]	6
Hydrofoil chord [m]	1
Hydrofoil area [m]	6

The lift and drag coefficients for the expected range of Reynolds number and the angle of attack have been provided by the CFD analysis and are presented in Appendix A: Hydrodynamic Coefficients. The type of hydrofoil considered for this study case is a Naca0015, which has a symmetrical shape.

4.1.1 Regular Wave

An Airy type regular wave is set in Orcaflex. The duration of the simulation for regular wave is set to 100s with a build-up duration of 30s. The build-up period introduces the wave dynamics smoothly from zero to their full values (see [7]). This period is set before the 0s simulation. This reduces transient responses and limits the need for long simulation run. The calculations duration is about 30s for this case. The time step is variable, with a maximum fixed to 0.25s (see [7]).

Table 6 - Properties of regular waves

Height [m]	3.0
Period [s]	10.0

4.1.2 Irregular Wave

The irregular waves set in Orcaflex are JONSWAP type, with only one wave direction. The wave parameters are presented in Table 7. More wave properties can be found in Appendix B: Wave Properties (irregular waves). The duration of the simulation is fixed to 30min and the build-up period to 160s. The time step is variable, with a maximum fixed to 0.25s (see [7]).

Table 7 - Properties of irregular waves

Hs [m]	1.5
ϒ [-]	1.0

Tp [s]	11.2603

4.2 FIRST RESULTS

The results presented in this study are focused on providing a validation of the global model architecture.

As explained section 3.3, it is assumed the device rotates with the wave (i.e. in the same direction as the orbital particle fluid motion), and that this rotation is positive around the local X axis. A positive torque is therefore expected. The Figure 5presents the orientation of the velocities and the lift coefficient expected. The orientation of the lift force F_L induces a positive moment on X local axis.

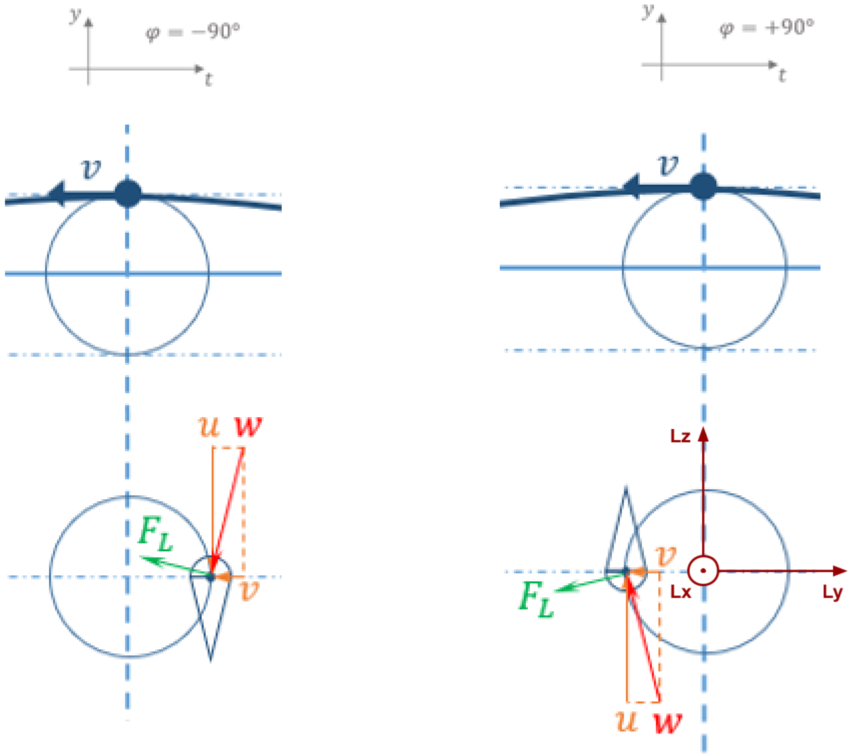

Figure 5 - Forces orientations in local axis (extracted from [6])

4.2.1 Regular Waves

Table 8 gives an overview of principal velocities:

Table 8 - Velocities of system and water particles for the regular wave

Item	Value	Note
Rotational velocity of the rotor [rad.s^{-1}]	0.63	Inverse of the wave period
Local velocity of the foil (from the rotation) [m.s^{-1}]	2.51	

Average magnitude velocity of water (at foils) [m.s^{-1}]	0.68	

Figure 6 shows the applied moment on the rotor. The moment is due to the drag and lift calculate on each hydrofoil, at every time step. As expected, the sign of the moment is positive, which is in phase with the rotation of the rotor.

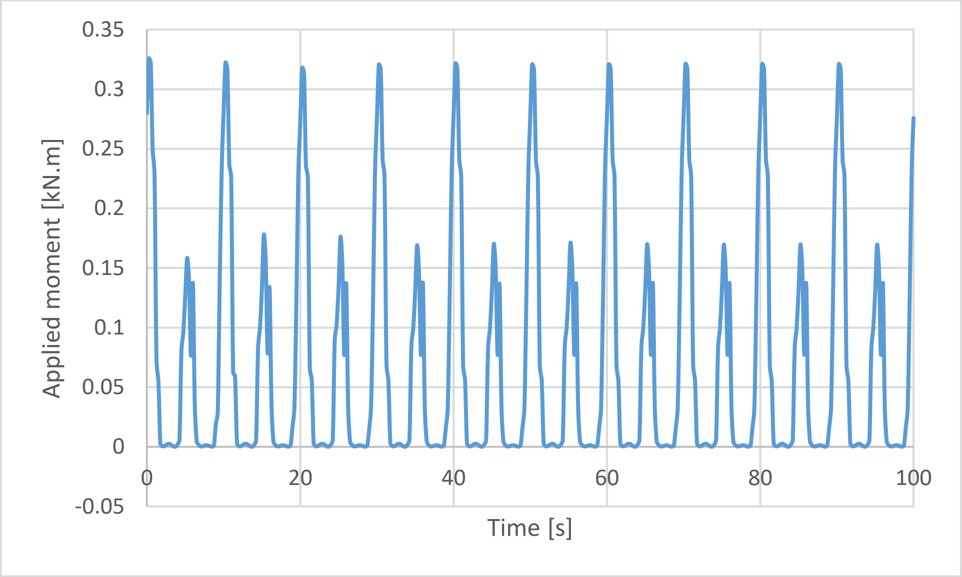

Figure 6 - Applied lift and drag moment on the rotor axis

Table 9 presents the principal results from the simulation. The Reynolds number and the attack angle β reached correspond to the data given in the hydrodynamic coefficients matrix, available in Appendix A: Hydrodynamic Coefficients.

The value of the drag is negligible compared to the lift.

Table 9 - Extrema and average values during a 100s simulation

	Average	Max	Min
Reynold number [-]	9.43e5	1.13e6	7.36e5
Attack angle of foils [deg]	0.09	16	-16
Relative inflow velocity [m.s-1]	2.55	3.05	1.99
Drag [kN]	1.33e-4	3.79e-4	4.23e-5
Lift [kN]	4.19e-2	1.70e-1	6.91e-5
Applied moment [kN.m]	7.11e-2	3.26e-1	1.27e-4

The lifts calculated on the two hydrofoils are close and follow the same variations. The Figure 7 highlights that the drag is negligible compared to the lift, during all the simulation.

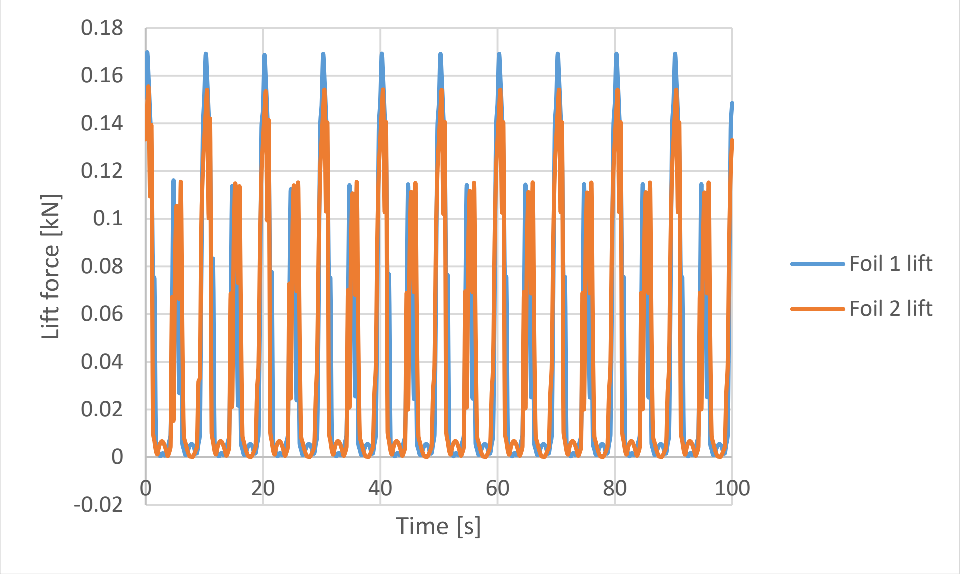

Figure 7 – Lift forces on hydrofoils

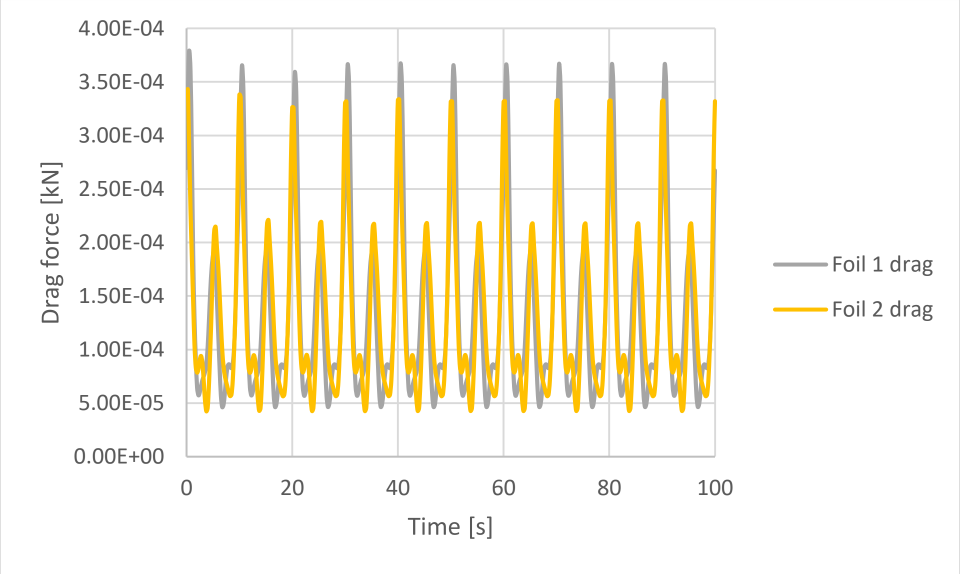

Figure 8 - Drag forces on hydrofoils

The Figure 9 and Figure 10 introduce the hydrodynamic coefficients associated to the lift and drag presented in Figure 7 and Figure 8.

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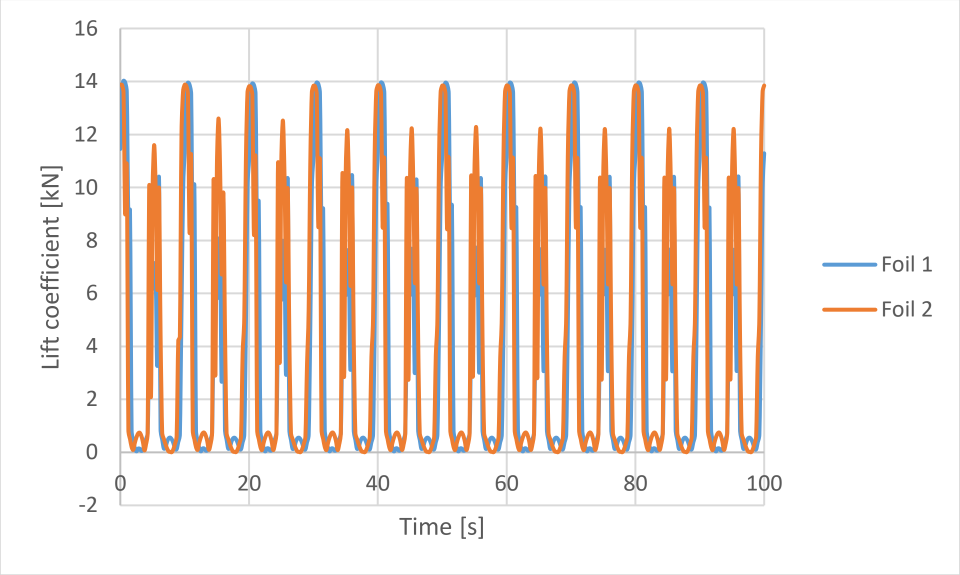

Figure 9 - Lift coefficient from hydrodynamic tabulation (see Appendix A)

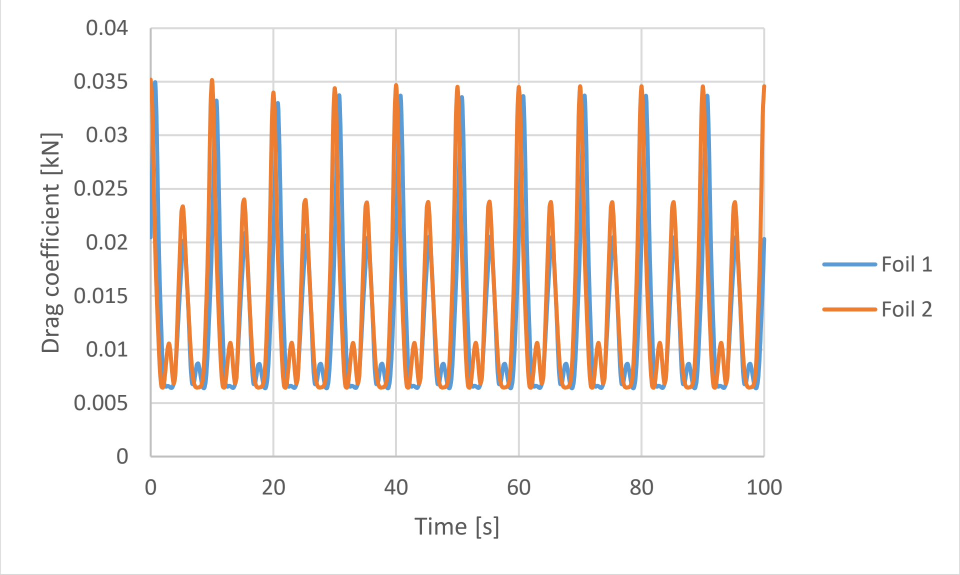

Figure 10 - Drag coefficient from hydrodynamic tabulation (see Appendix A)

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The velocity of the hydrofoils driven by rotation is constant during the simulation, to allows the hydrofoils to be in phase with the waves.

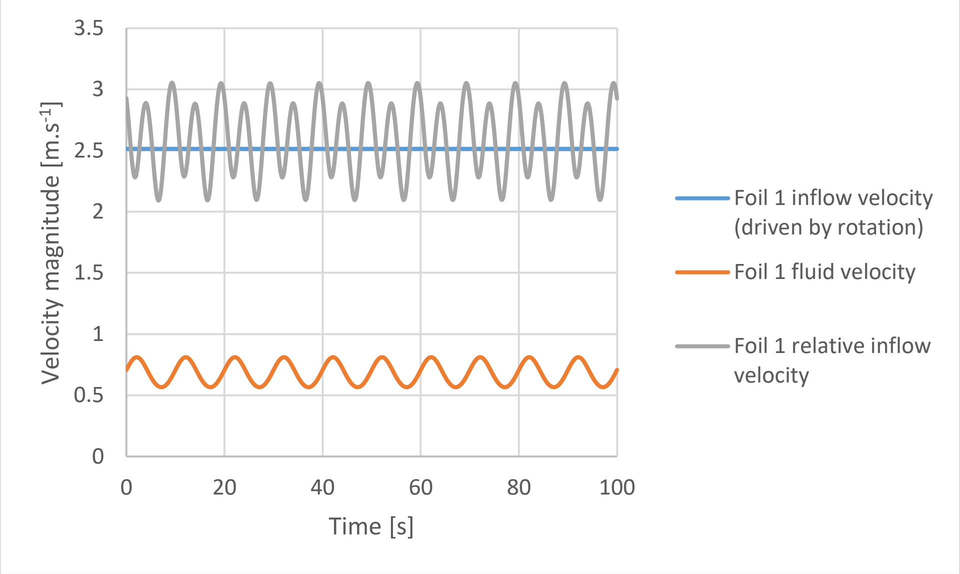

Figure 11 - Magnitude of velocities

The Figure 12 presents the attack angle β of the hydrofoils, which correspond to the angles available in the hydrodynamic coefficient tabulation (see Appendix A: Hydrodynamic Coefficients). No extrapolation is therefore needed to obtain the lift and drag coefficient.

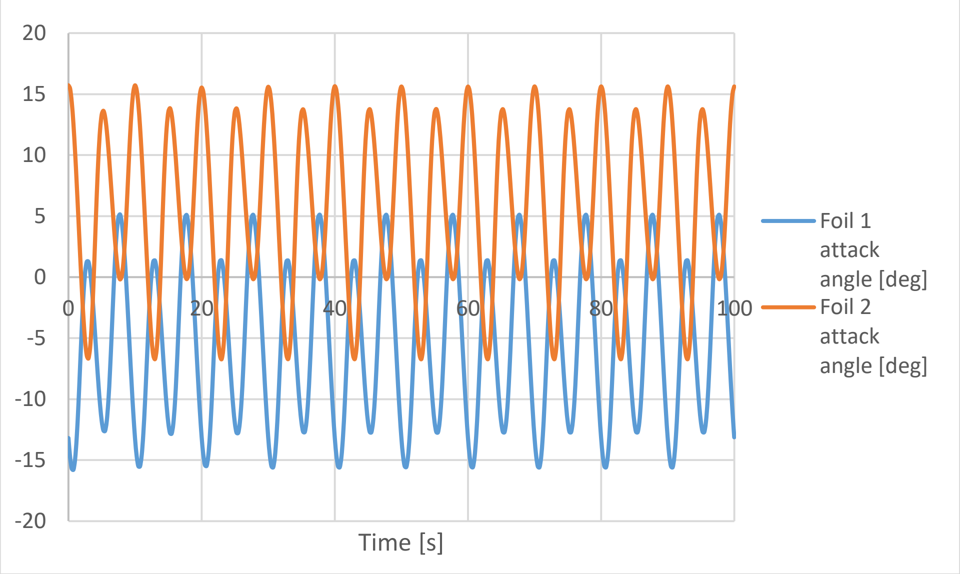

Figure 12 - Attack angle of the hydrofoils

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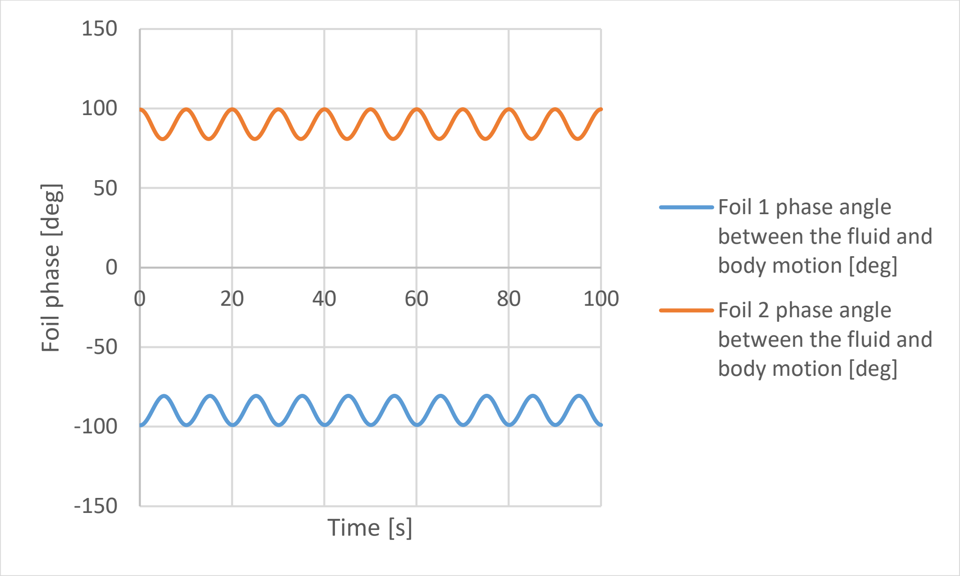

Figure 13 - Phase angle between the fluid velocity and the foil motion

The Figure 13 shows that the phases of foils oscillate around ±90°. The angular velocity of the rotor has been chosen to respect those phases. The oscillation is due to the radius of the system and the motion of the rotor.

The Figure 14, Figure 15 and Figure 16 present the displacements of the rotor and the support structure.

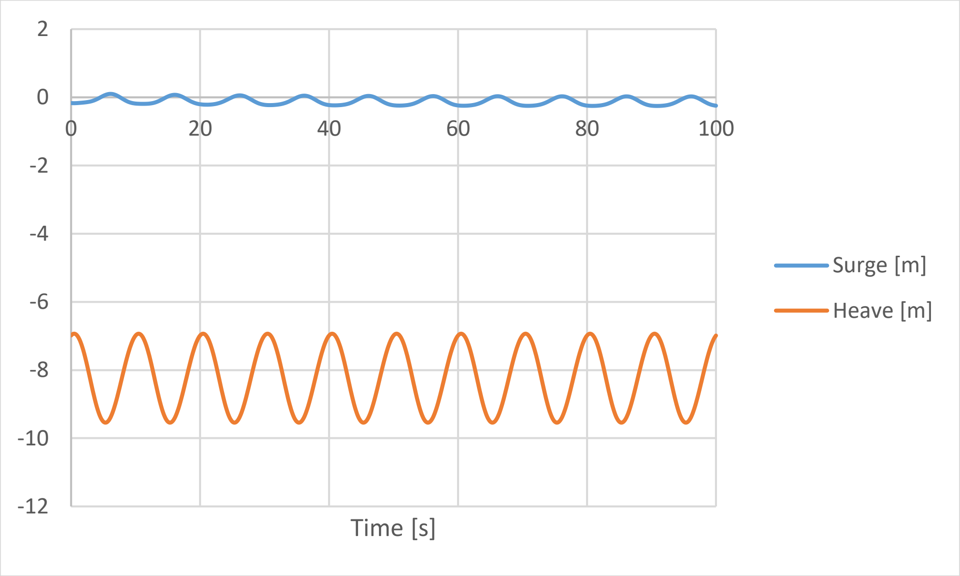

Figure 14 - Heave and surge of the rotor axis

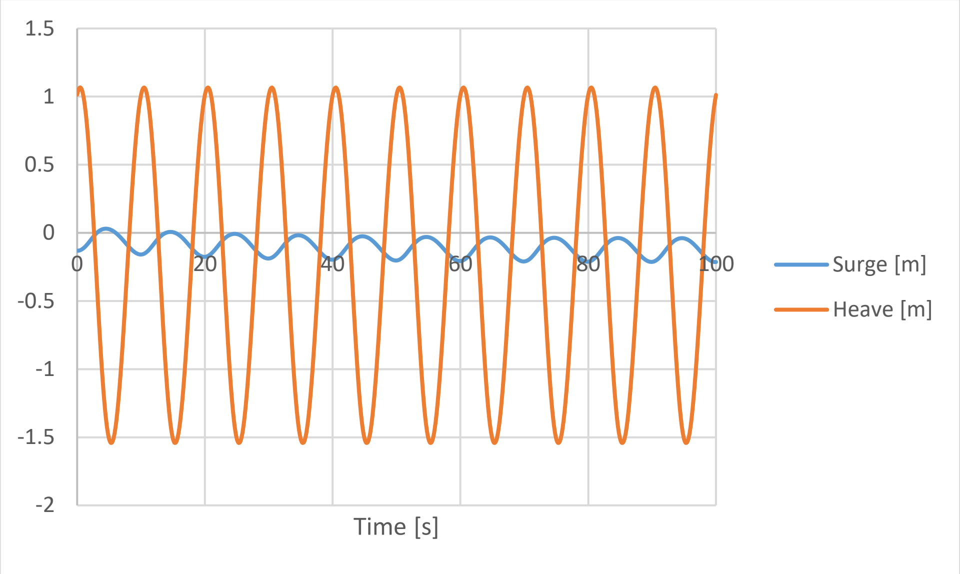

Figure 15 - Translations of the floater

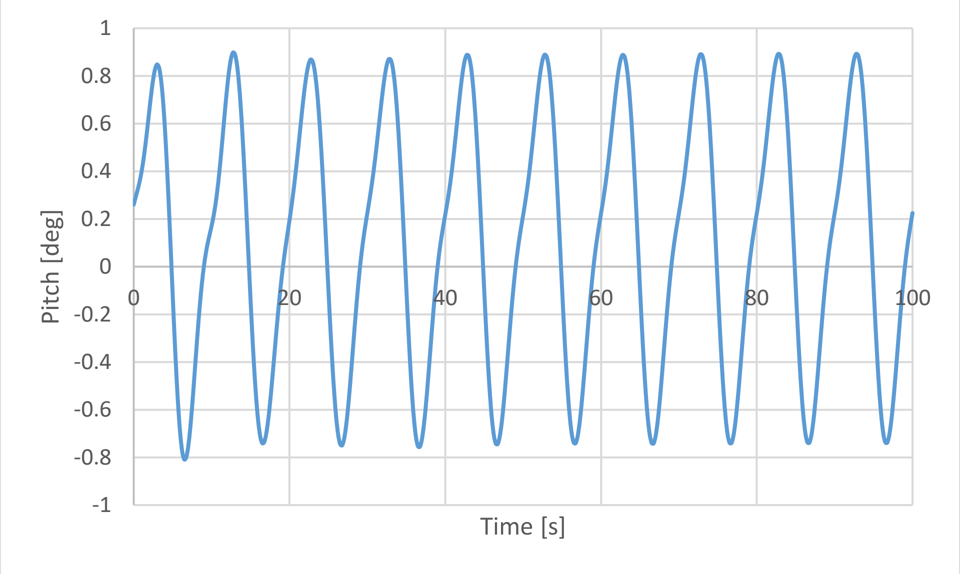

Figure 16 - Rotation of the floater

4.2.2 Irregular Waves

The simulation of the system submitted to irregular waves is set with a build-up of 160s and a stage of 30min. The calculations duration is about 5min for this case. Complete information about the wave can be found in Appendix B: Wave Properties (irregular waves). All the graphs introduced in this section present the first 200s of the simulation (after the build-up stage).

Table 10 - Main velocities magnitudes

Item	Value	Note
Rotational velocity of the rotor [rad.s^{-1}]	0.72	Inverse of the mean wave period T1 (see [9])

Local velocity of the foil (from the rotation) [m.s^{-1}]	2.88	
Average magnitude velocity of water (at foils) [m.s^{-1}]	0.20	

As for the regular wave, the trend of the applied moment is positive, which corresponds to the rotation of the device in local frame. The Figure 17 shows that the moment induced by the hydrofoils hydrodynamic remains closed to zero during most of the simulation, excepted for some peaks reached when the angle of attack induces higher lift coefficients (from 6e-3 to 1e1 ; see Figure 20, Figure 24 and Appendix A: Hydrodynamic Coefficients).

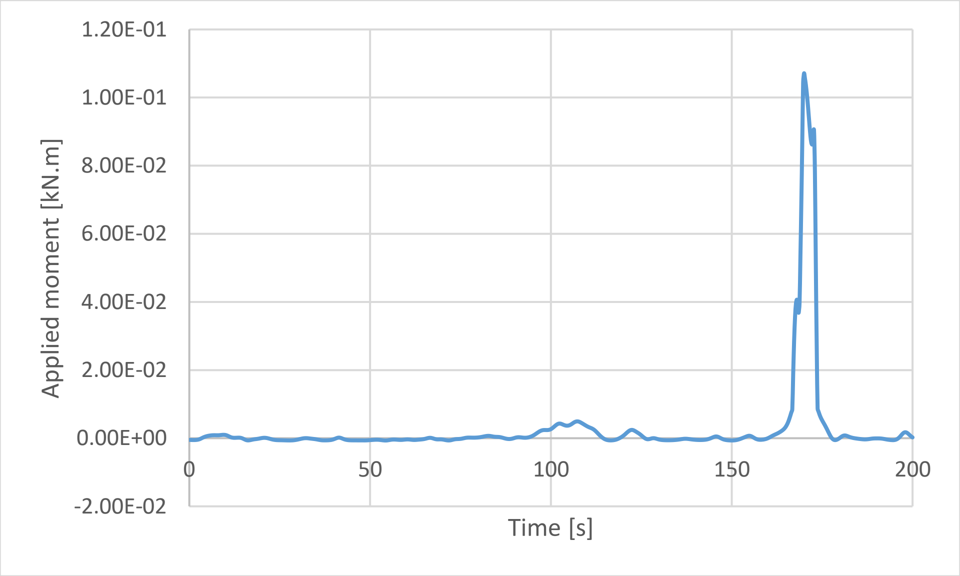

Figure 17 - Applied moment on the rotor due to hydrofoils hydrodynamic

The values of outputs between regular and irregular waves are not comparable, because sea state and the angular velocity of the device are not the same. However, it can be useful to highlight that an irregular wave gives a better vision of the device comportment in real conditions.

Table 11 - Extrema and average values during a 30min simulation

	Average	Max	Min
Reynold number [-]	1.07e6	1.28e6	8.29e5
Attack angle of foils [deg]	-0.06	12.18	-13.13
Inflow velocity w [m.s-1]	2.89	3.45	2.24

Drag [kN]	9.20e-5	2.61e-4	5.12e-5
Lift [kN]	4.91e-3	1.75e-1	3.22e-7
Applied moment [kN.m]	3.16e-3	1.40e-1	-6.75e-4

As for the regular waves, the drag on hydrofoils seems to be negligible in comparison with the lift (see Table 11, Figure 18 and Figure 19).

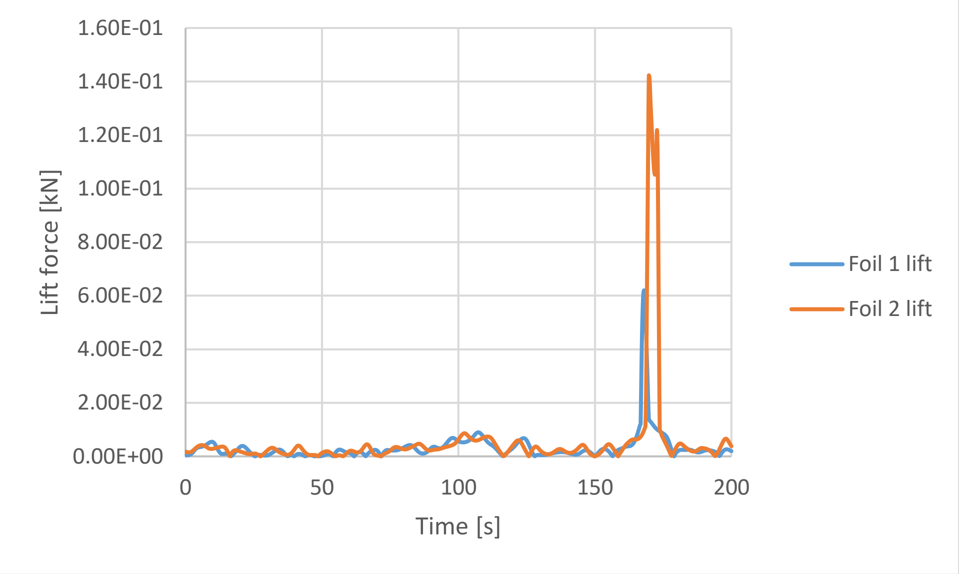

Figure 18 – Lift forces on hydrofoils

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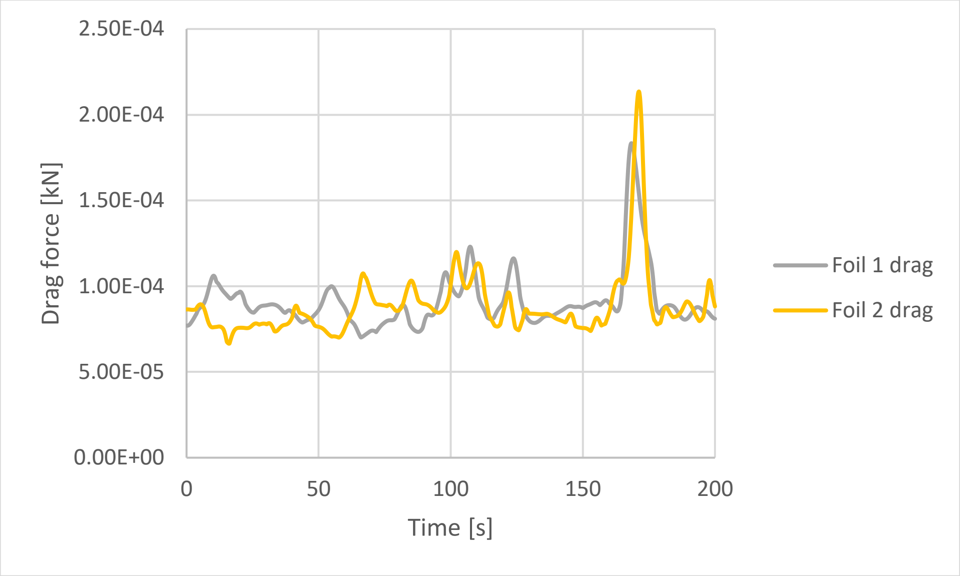

Figure 19 - Drag forces on hydrofoils

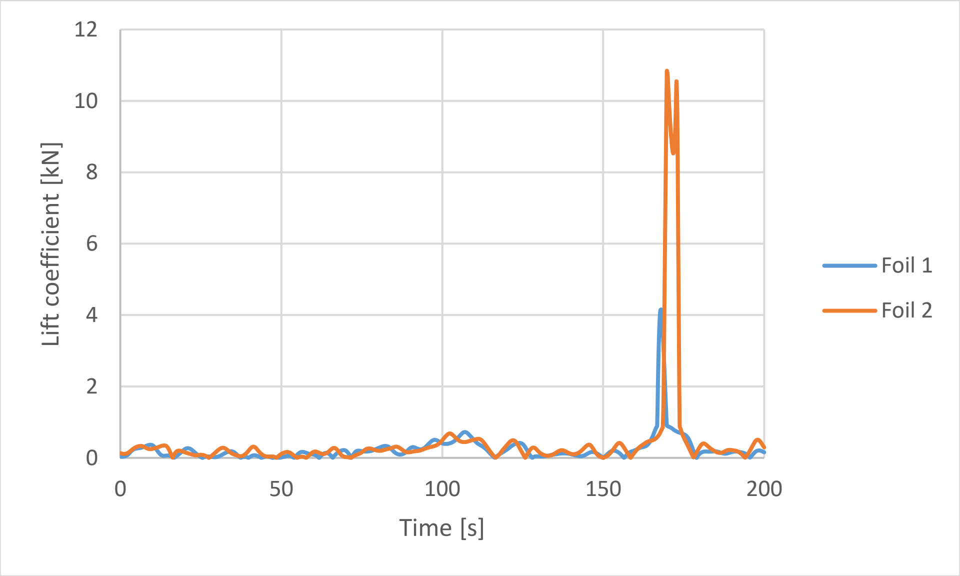

Figure 20- Lift coefficient from hydrodynamic tabulation (see Appendix A: Hydrodynamic Coefficients)

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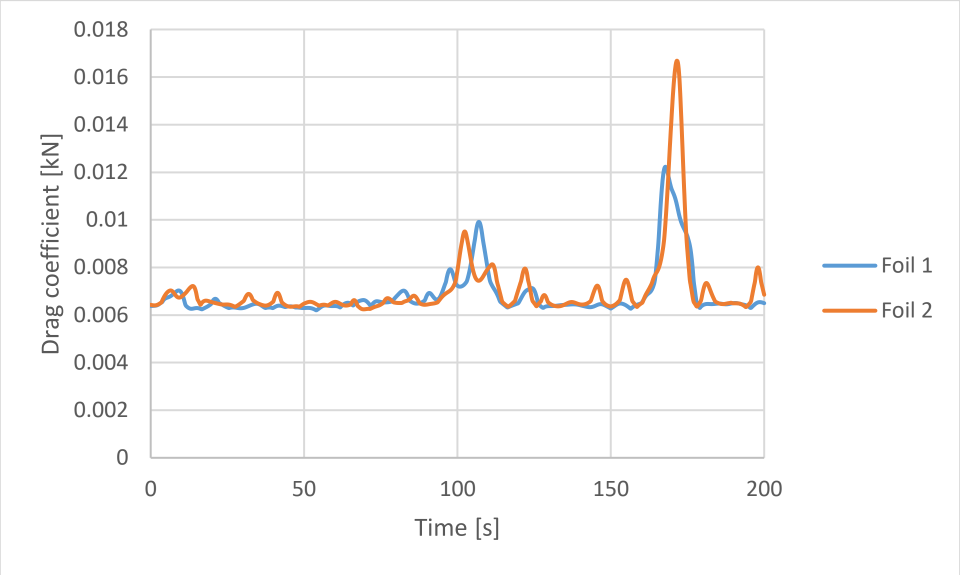

Figure 21 - Drag coefficient from hydrodynamic tabulation (see Appendix A)

The fixed rotational velocity of the device does not allow a constant phase angle between the fluid and the body motion. The chosen value of the rotational velocity should be redefined for the irregular wave.

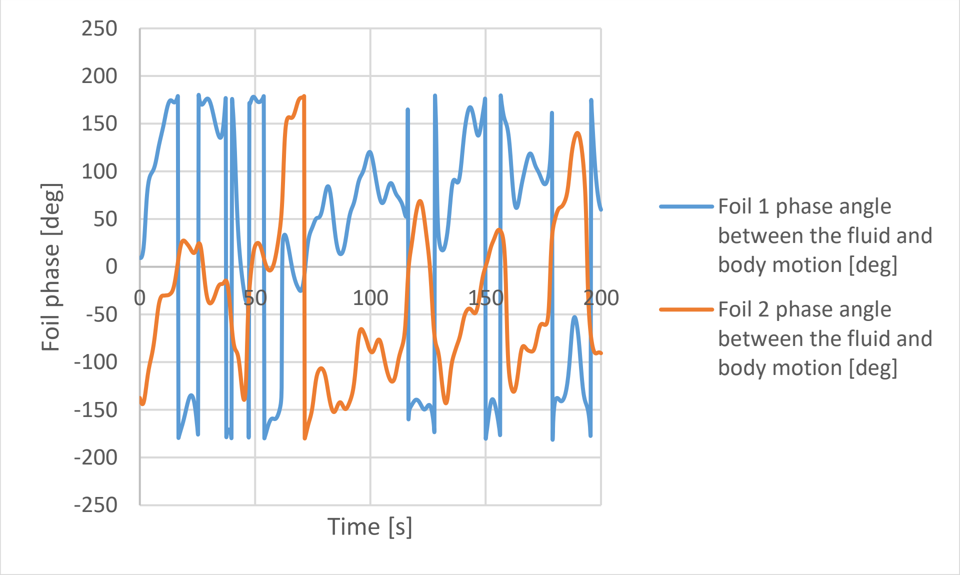

Figure 22 - Phase angle between the fluid and the hydrofoils motion

The Figure 23 presents the magnitude of velocities in the global coordinate system.

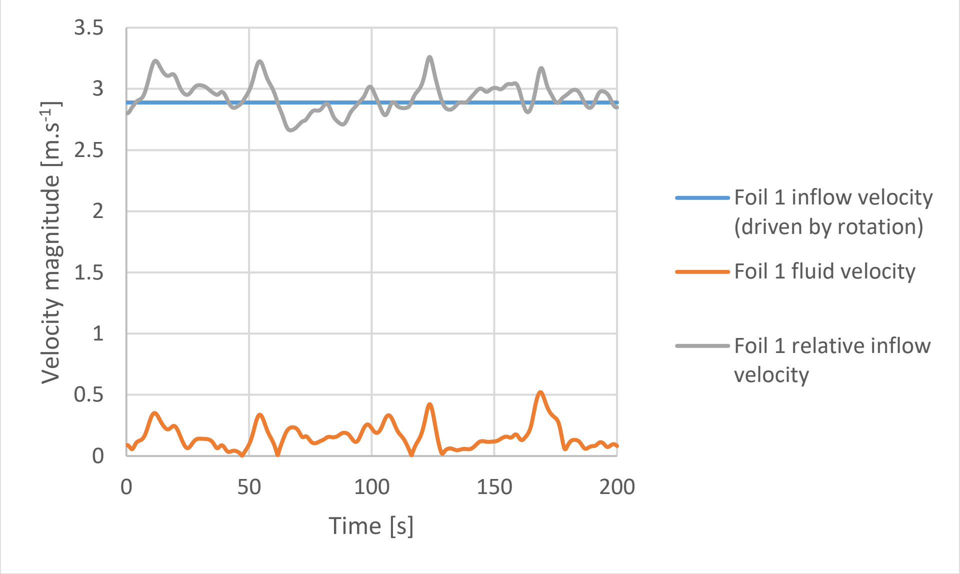

Figure 23 - Magnitude of velocities

The angle of attack β of the hydrofoils has a major influence on the value of the hydrodynamic coefficient. Its variation during a 200s period of simulation is presented Figure 24.

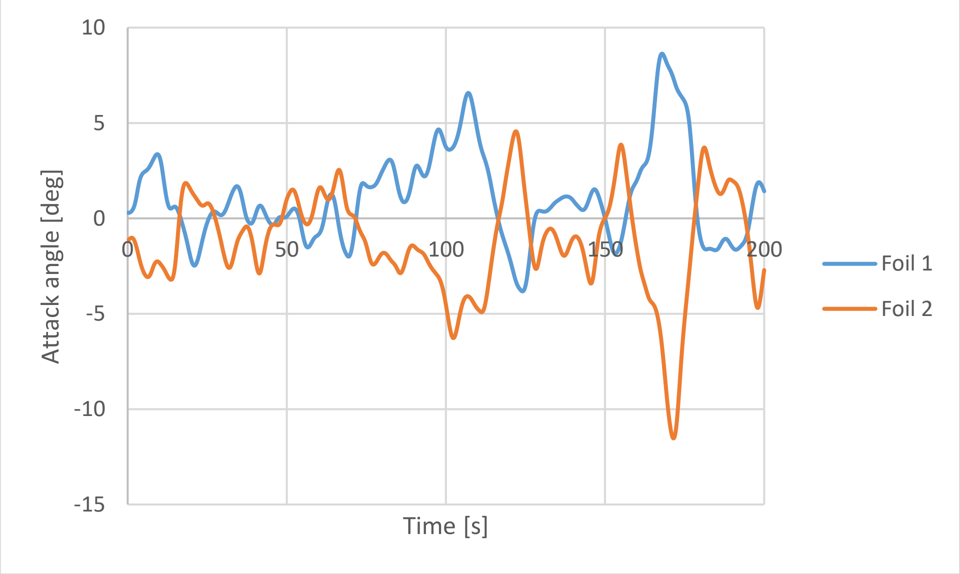

Figure 24 - Attack angle of hydrofoils

The Figure 25, Figure 26 and Figure 27 present the displacement of the device and the floater during a 200s period of the simulation.

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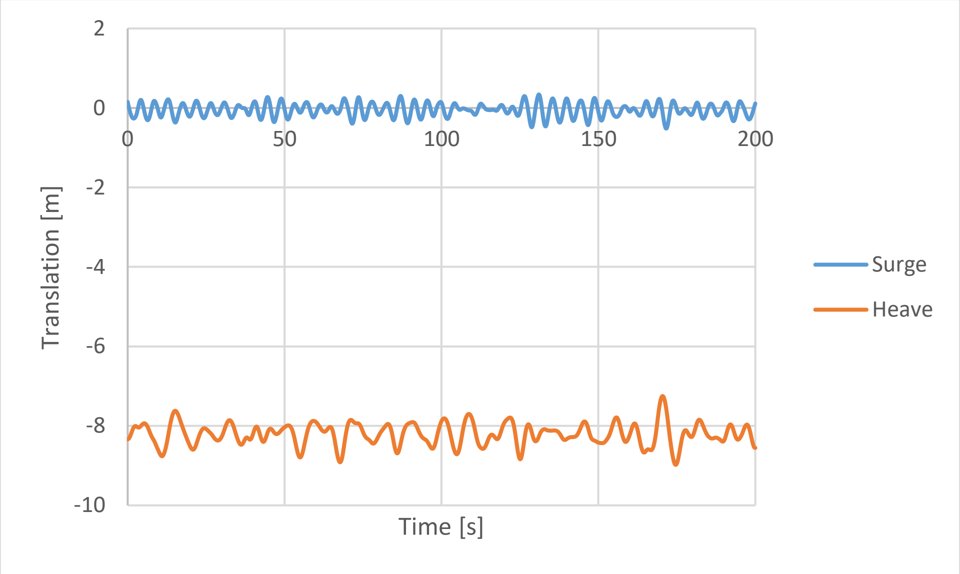

Figure 25 - Heave and surge of the rotor axis

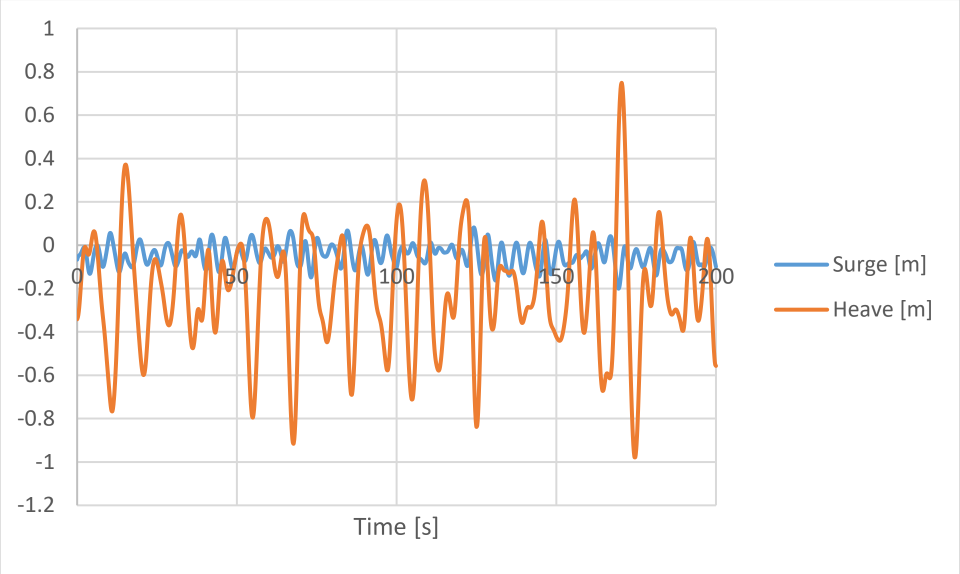

Figure 26 - Translations of the floater

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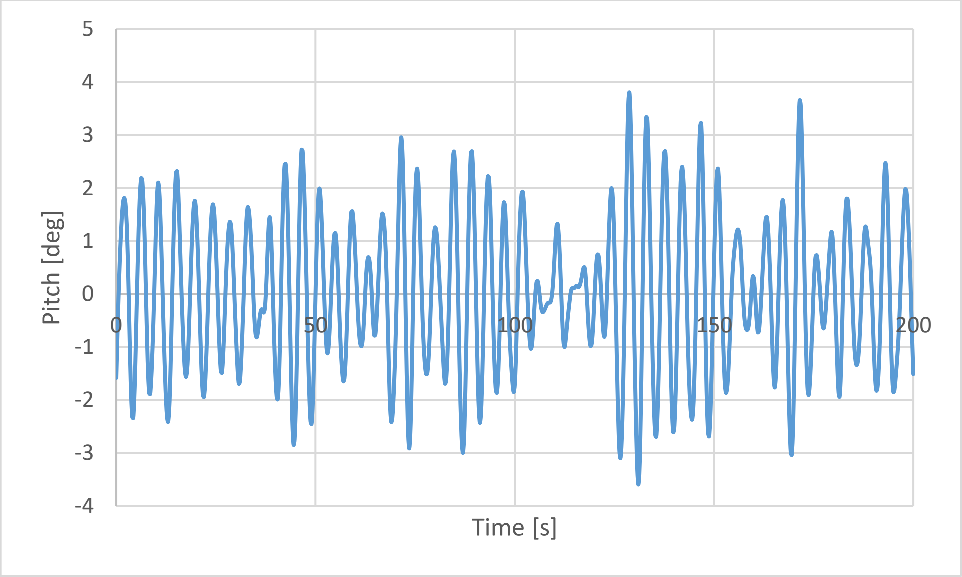

Figure 27 - Rotation of the floater

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5 FUTURE

5.1 APPLICATION OF THE MODEL

This model should provide a global view of the system. The rotor and supporting structure hydrodynamics are considered and coupled, and a simplified model of the moorings will be integrated if required.

This model aims to provide a global approach of the system performance. It will be able to supply the forces between the bodies of the system:

- Forces between the rotor and the floater/substructure
- Forces between the foil(s) and the rotor axis
- Forces between the floater/substructure and the mooring lines
- Global linear mooring line loads

This model will be able to handle a control strategy, as:

- Adapt the rotation velocity of the rotor
- Adapt the radius between the hydrofoils and the rotor axis
- Control the pitch of the foils

The control strategy will be provided by the WP5.

5.2 EVOLUTION OF THE MODEL

The usage of the current model is limited to INNOSEA, using Orcaflex. It is only a version used to the demonstration of the model. After validation, a fuller model will be developed with another framework allowing different partners in the team to run it.

Orcaflex is used for the dynamic analysis, a future version of the model must be functional without this software. To catch the objectives described in section 5.1, the model should be able to do a time domain dynamic analysis. An equation of motion will be defined and resolve in the model:

$$M(p,a) + C(p,v) + K(p) = F(p,v,t)$$

where $M(p,a)$ is the system inertia load, $C(p,v)$ is the system damping load, $K(p)$ is the system stiffness load, $F(p,v,t)$ is the external load ; p, v and a are the position, velocity and acceleration vectors, and t is the simulation time.

A type of resolution, with the solver selection, need to be defined, and implemented.

In the current model, the definition of the environment is handled by Orcaflex. The final model will allow the user to defined different type of waves, choosing the period, the height, the direction…

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As explained in section 5.1, the model will be able to interact with control external function.

The full model may be developed in Python 3, and a discussion is in progress about the interface between the WP5 and the global model.

This model must be easy for collaborators to use. A use case and a brief manual will support every deliverable version of the model.

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APPENDIX A: HYDRODYNAMIC COEFFICIENTS

Table 12 - Drag coefficients matrix

		Reynolds number [-]										
		5,00E+04	7,90E+04	1,26E+05	1,99E+05	3,15E+05	5,00E+05	7,92E+05	1,26E+06	1,99E+06	3,16E+06	5,00E+06
Angle of attack β	0	0,03067	0,02412	0,01559	0,01076	0,00851	0,00731	0,00659	0,00613	0,00582	0,00562	0,00548
	2	0,0282	0,02005	0,016	0,01186	0,00917	0,00769	0,00685	0,00634	0,00602	0,00582	0,00567
	4	0,02728	0,01997	0,01624	0,01368	0,01106	0,00904	0,00785	0,00711	0,0067	0,00641	0,00621
	6	0,03023	0,02263	0,01827	0,01551	0,0135	0,01148	0,00981	0,00868	0,00796	0,00748	0,00709
	8	0,03879	0,02853	0,0229	0,01911	0,01642	0,01435	0,01259	0,011	0,00977	0,00892	0,00827
	10	0,05827	0,03905	0,02997	0,02442	0,02038	0,01746	0,01532	0,01366	0,01215	0,01088	0,00986
	12	0,14208	0,05792	0,04086	0,03167	0,02665	0,02223	0,01881	0,01637	0,01458	0,01319	0,01202
	14	0,16827	0,14693	0,0598	0,0435	0,03719	0,03138	0,02554	0,02089	0,018	0,01602	0,0145
	16	0,19581	0,16474	0,18262	0,06837	0,05485	0,04963	0,03973	0,02988	0,02421	0,02064	0,01823
	18	0,21799	0,18286	0,20985	0,17621	0,08317	0,08375	0,06925	0,05137	0,03792	0,03043	0,02535
	20	0,24219	0,20116	0,23691	0,19684	0,22668	0,11896	0,11111	0,09319	0,06776	0,05068	0,04007

Table 13 - Lift coefficients matrix

		Reynolds number [-]										
Angle of attack β		5,00E+04	7,90E+04	1,26E+05	1,99E+05	3,15E+05	5,00E+05	7,92E+05	1,26E+06	1,99E+06	3,16E+06	5,00E+06
	0	0	0	0	0	0	0	0	0	0	0	0
	2	0,436	0,4622	0,3187	0,2263	0,2088	0,2113	0,2159	0,2203	0,2235	0,2257	0,2275
	4	0,6027	0,6107	0,6097	0,5392	0,4603	0,424	0,4283	0,437	0,4433	0,4486	0,4524
	6	0,7467	0,7542	0,7571	0,7669	0,7658	0,6956	0,6526	0,6457	0,6571	0,6663	0,6738
	8	0,8681	0,8856	0,8822	0,8911	0,916	0,9451	0,9257	0,8896	0,8683	0,8762	0,8898
	10	0,8991	10,142	10,122	10,051	10,277	10,652	10,988	11,303	11,211	11,021	10,974
	12	0,5366	10,343	11,421	11,139	11,202	11,684	1,222	12,629	12,909	1,317	1,332
	14	0,5729	0,4071	11,015	11,857	11,965	12,479	13,157	13,813	14,278	14,647	14,952
	16	0,6367	0,4324	0,6452	11,454	12,275	12,767	13,678	14,662	15,349	15,859	16,254
	18	0,6871	0,4569	0,6983	0,4645	12,028	10,439	13,334	14,711	15,873	16,634	17,238
	20	0,7522	0,4805	0,7761	0,5189	0,7794	0,9286	12,432	1,365	15,416	16,745	17,683

APPENDIX B: WAVE PROPERTIES (IRREGULAR WAVES)

Table 14 - Wave properties of irregular wave (from Orcaflex)

Parameter	Value
Wave train name	Wave1
Wave type	JONSWAP
Number of components	217
Seed	1,23E+04
Hs (m)	1,5
Tz (s)	8
T1 (s)	8,70049027
Parameters	Partially specified
γ	1
α	7,09E-04
σ1	0,07
σ2	0,09
fm (Hz)	0,0888075
Tp (s)	11,2603102
Frequency spectrum discretisation method	Equal energy
Min. rel. freq.	0,5
Max. rel. freq.	10
Max. component freq. range (Hz)	0,05
Spectral moments:	
m0	0,14055719
m1	0,01615509
m2	0,00216932
m3	3,73E-04
m4	9,19E-05
Bandwidth (ε)	0,79735192

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