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Original
Wave energy converter mooring system: Available solvers and model validation / Paduano, B.; Moscoloni, C.; Fenu, B.; Orlando, V.; Giorcelli, E.; Bracco, G.; Mattiazzo, G.. - (2021), pp. 2088-2088-8. (Intervento presentato al convegno 14th European Wave and Tidal Energy Conference, EWTEC 2021 nel 2021).

Publisher:
European Wave and Tidal Energy Conference Series

Published
DOI:

Wave Energy Converter mooring system: available solvers and model validation

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Abstract—**Talking about mooring systems for Wave Energy Converter shall be taken into account not only the station-keeping problem but also the influence of the mooring on the device motion. In literature several software for mooring modeling could be investigated, and among these software MoorDyn should be considered for its versatility. By the way, each model should be validated against experimental data to test its reliability hence, the aim of these paper is to follow the analysis which starts from an overview of the mooring system models and software and which ends with a model validation which has been performed against the experimental data obtained during Naples experimental campaign. Device kinematic has been recorded through a data acquisition system equipped in the scaled wave energy converter, and it has been used as input of the numerical simulation. The force recorded with a load cells system, connected with the mooring lines and the device, has been compared with the numerical one, derived from MoorDyn, and they have shown a marked overlapping that witnesses the validation.**

Index Terms—**ISWEC (Inertial Sea Wave Energy Converter), Mooring, MoorDyn**

I. INTRODUCTION

THe mooring system holds an important role in Wave Energy Converter (WEC) design field, because its action is not limited to the purpose of station keeping, but it must not affect the energy harvesting process, in particular in the case of Wave Active Bodies [1]. It goes without saying that the main aspects and capabilities of a mooring system [2] involve more complex points discussed in the following:

- Each component of mooring system must withstand at environmental loads during all lifetime.
- Ensure the capability of WEC device to weathervane.
- Be economical.
- Ensure ease of monitoring and maintaining.
- Reduce environmental impacts with seabed.

The above-mentioned key points give an idea of implications and contact points that the design of a mooring system has into a whole WEC design cycle, from the logistical and economical aspects to the estimation of the forces involved on the energy devices and on the environmental impact. These factors have different weights depending on the scenario in which the device is involved.

The mooring system design of WECs is a complex system design that takes into account the WECs' characteristics, the environmental conditions and the operational requirements. To explain the mooring system behaviour it is necessary to apply numerical models able to describe the forces acting of the energy device [3].

Due to the complexity of the mooring system hydrodynamics, it is necessary the use of specific software to solve non-linear numerical models. In reason of that, a preliminary screening of the software available on the global panorama, including open source and the commercial software, represents an unavoidable starting point. The software analysis will rotate around three fundamental key points: the implementation of the hydrodynamic inputs, the cable solver features and the open source availability.

The following sections have in charge of discussing the advantages and the drawbacks that have justified the software choice. A panoramic of the Inertial Sea Wave Energy Converter (ISWEC) device is presented to convey the working principle of the device and the mooring configuration, which is the core around which the paper swivels. At last, after the software and the physical environments are consolidated, the validation of the mooring system is discussed.

II. ISWEC DEVICE

A wave energy converter is a complex system that produces electric energy combining the waves motions and the dynamic behaviour of the device. How the mooring system acts on the energy conversion device influences the electrical power produced and the global performance of the device, so it is important to understand the WEC working principle. In this section the ISWEC system is presented with reference to Figure 1. ISWEC is an energy harvesting device designed to convert the wave energy through the gyroscopic effect of a flywheel [4] [5]. The system produces electric energy because of the presence of one or more gyroscopic groups that, via the coupling between the hull's pitching dynamic and the flywheel rotational motion, generate gyroscopic forces converted into electric energy by a Power Take-Off (PTO). Due to the corrosive conditions in which the system operates, each mechanical part is sealed in the hull's volume that interfaces with the sea waves.

The incident waves cause the pitch motion of the hull, δ, that induces a precession oscillation ϵ of the gyroscope. Damping the precession of the gyroscope, the system achieves the extraction of energy by the PTO, an electrical torque generator, connected to the gyroscope support through a gearbox. The non-linear

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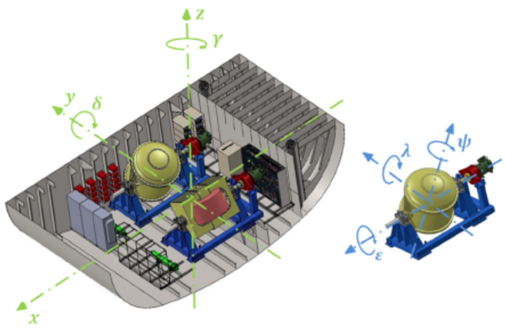

Fig. 1. ISWEC Device concept.

equation relates the gyroscopic torque to the pitch motion [6].

$$T_\epsilon = I_g \ddot{\epsilon} + (I_g - J_g)\dot{\delta}^2 \sin\epsilon \cos\epsilon \\ - J_g \dot{\phi}\dot{\delta} \cos\epsilon \qquad (1)$$

Where:

- T_ϵ is the torque at PTO
- I_g is the inertia momentum around PTO axis
- $\dot{\phi}$ is the velocity of the flywheel
- J_g is the flywheel momentum of inertia

The best performances are obtained by the control of the PTO torque and by a proper synchronization of the incoming sea state with the spinning speed of the flywheel.

Considering the ISWEC working principle, the mooring system must guarantee the station-keeping and the weather-vaning of the device, maintain a passive behaviour minimizing the interference with the device motion on what concern the pitch motion, and on the contrary, constrain the horizontal motion. In reason of that, the motion regimes are strongly time-dependent, and this affects the choice of the best representation model, as discussed in the following.

III. MOORING MODELS

A mooring system can be modelled in term of time-dependency and it is particularly interesting evaluate the relationship between the coupling of mooring system model and WEC model solvers. In this section different types of models are presented, categorized as static, quasi-static, and dynamic [7].

- Static
- Quasi-Static model
- Dynamic model

A **Static model** only treats constant loads, such as buoyancy, gravity, wind, varying non-time current, and mean forces of wave drift. The equilibrium between the constant loads and and the mooring lines restoring force upon a conversion device is considered.

In a **Quasi-Static model** inertia forces are not considered. The system motion is continuous and linear among two static locations over a particular time phase in which the loads are kept constant. This approach does not consider the dynamic effects on the mooring system, neglecting the motion reliance on damping, acceleration of fluid and mass. This modelling strategy had particular effectiveness in the design of the static offshore structure and on what concerns the mooring systems in which there are taut lines.

Instead, **Dynamic Model** resolves the equations of motion across all degrees of freedom and considers all dynamic effects mentioned above. This modelling approach becomes essential for our purposes to face the International Standards requirements about the inertia forces included into the analysis [8]. Generally, each software is based on a formulation of Morison's Equation [9] for slender body considering added mass and drag coefficient as shown in (2).

$$F(t) = \frac{\pi}{4}\rho C_M D^2 \dot{u}(t) + \frac{1}{2}\rho C_D D u(t)\,|u| \qquad (2)$$

Besides, the analysis on a mooring system can be performed in two different ways [10]:

- Uncoupled analysis
- Coupled analysis

In **Uncoupled analysis** the motions of WEC and the mooring system are simulated separately and only a time-domain approach can be used. This approach of simulation should be used in a design workflow that considers a static device, in which there is no mutual influence between mooring system and the device.

Instead, **Coupled analysis** is characterized by mutual communication at each time step between the mooring solver and the WEC hydrodynamic solver, in which the generated force is swapped. This simulation can be performed both in time-domain and in frequency-domain. However, it is important to highlight that an uncoupled simulation is useful to validate an experimental campaign as shown in the following, but can't be used to design a mooring system.

Another important parameter that should be taken in consideration is represented by the model implementation technique. In **lumped-mass** method (LM) the mooring line is divided into a series of nodes with concentrated mass M, connected through a springs and dampers system. In **Finite Element** (FE) analysis, instead, mooring lines are modelled with elements characterized by a distributed mass and axial stiffness, therefore each element is represented by a function of order higher than 1. In this case, is simple to understand that FE model reaches spatial convergence faster than LM model, but it can be computationally expensive.

The different approaches to properly model the mooring system have been presented. A review of the available software is presented in the next paragraph.

IV. SOFTWARE REVIEW

The following section aims to generate a compendium of the software available in literature.

Table (I) reports some of the most used software [2] to manage the behaviour of the mooring system. **Aqwa** is developed by ANSYS [11] to resolve hydrodynamic problems of offshore units. It is suitable to resolve

TABLE I
MOORING SOLVER

-	Software	Commercial Developer
1	Aqwa	ANSYS
2	Orcaflex	Orcina
3	SeaFEM	Compass
4	SESAM	DNV-GL
5	MoorDyn	-
6	Moody	-

WEC dynamic problem and mooring dynamic problem using LM method.

Orcaflex is developed by Orcina [12] and it is one of the most used software to simulate hydrodynamic models in the wind and wave offshore field. It computes WEC and mooring dynamic behaviour.

SeaFEM, developed by Compass, resolves a 3D FE model used to describe the fluid-structure interaction problem between fluid and floating body.

SESAM is a group of softwares developed by DNV-GL [13]. It includes HydroD for hydrodynamic and DeepC for mooring analysis which communicates through SESAM interface.

MoorDyn is an open-source software developed by Matthew Hall from Main University [14]. It is only a cable solver and does not resolve WEC dynamics, but can be coupled with WEC-SIM or in Matlab/Simulink environment.

At the end, **Moody** is an in-house software from Chalmer's University, developed by Johannes Palm and Claes Eskilsson [15]. It is a cable solver, but it can be coupled with Matlab interface or with an automated program interface (API).

Due to the complexity of the problem represented by the interaction between the mooring system with the physical environment made by the floating WECs and by external forces, it is really important underlying that most of the above-mentioned software are not only cable solvers, but also embed hydrodynamic solvers. Each hydrodynamic tool is analysed with the aim of having an overview of which software is functional to the resolution of a given problem and the best hydrodynamic representation of it. In II are reported some important features [16]. The first evaluation criteria that have to be considered is the capability of the software to solve regular and irregular waves. Another distinction should be made in terms of software capability to compute the hydrodynamic loads in Diffraction/Radiation and to estimate added mass and damping coefficient matrix starting from a generic input by itself or is needed to insert these parameters as input. How it is shown, **ANSYS** package is able to compute these parameters by itself, just like **SeaFEM** and **SESAM** too, with HydroD package. On the other hand, **Orcaflex** needs a pipe with another software to receive these parameters in input.

After a first screening of the most important features of each software, the paper would be like to analyse the cable solver capabilities of each software [17]. The first software feature considered in our survey is the capability of the software to implement the **cable stiffness**. The mooring international standards [8] prescribe that bending and torsional stiffness can be neglected generally, on the other hand in fatigue analysis they act a significant role and they can induce an important variation on axial stresses [18].

The lines of the mooring system, especially in an FEA environment, should be described using a non-linear approach under the point of view of the behaviour of the structural component, indeed a cable can react to tensile stresses only, for example, a synthetic rope shows a non-linear load-strain curve. This attitude can be modelled and implemented in the software environment through a load-strain curve (axial). The most common way in which it is possible to describe a cable behaviour is to insert a non-linear, or bi-linear, load-strain curve. The capability of the software to implement this feature can be determinant for analysis's purposes.

At last, the **spatial order**, just for FE method based software, represents an important key to interpretation in the evaluation of the software performances. Indeed, the spatial order represents how an element can be modelled. . It goes without saying that FE method has characterized by a better spatial convergence than LM, besides the spatial convergence is also faster, as well as the higher spatial order.

An exception is represented by MooDy that uses a p^{th} order.

A. Non-Linearities

In the previous paragraph, just a material non-linearity is reported. But the mooring design field is characterized by multiple kinds of non-linear behaviours caused by different sources. For this reason, a deepening is needed.

- Material non-linearities (Stiffness).
- Geometric non-linearities (Mooring system resonance).
- Viscous non-linearities.

Material non-linearities, as said previously, derive from the typical behaviour of a cable that acts under tensile stress only. This mechanical attitude translates with a non-linear load-strain characteristic, for instance this is clearly shown by the analysis of a nylon rope [19]. The presence of the time variable enlightens another important effect of the axial stiffness behaviour, indeed cyclic loads can significantly reduce elongation capacity of the synthetic rope. Due to that the rule [8] also requires an axial stiffness after cyclic load condition.

Geometric non-linearities can characterize the whole mooring system or a single part of it, due to the action of the current drag forces that can induce VIV (Vortex Induced Vibration) or VIM (Vortex Induced

TABLE II
HYDRODYNAMIC SOLVER

	Wave		Hydrodynamic		
	Regular	Irregular	D/R Loads	D/R Input	Morison Input
Aqwa	v	v	v	x	v
Orcaflex	v	v	x	v	v
SeaFEM	v	v	v	x	v
SESAM	v	v	v	x	v

TABLE III
CABLE SOLVER FEATURES

	Stiffness					
	Axial	Torsional	Bending	Spatial Order	LM/FE	Load-strain curve
Aqwa	v	x	v	-	LM	v
Orcaflex	v	v	v	-	LM	v
SeaFEM	v	x	x	2	FE	x
SESAM	v	v	v	2	FE	v
MoorDyn	v	x	x	-	LM	x
Moody	v	x	x	p	FE	x

Motion). These forces are born from the relative velocity between the mooring line and the water: a simple way to avoid this issue is represented by the rule for slack mooring system.
Viscous non-linearities are in charge of the dependence of the drag coefficient from the Reynolds number. This connection [19] shows how this dependence should be considered, despite most of the software cited neglect it.

V. MOORDYN

The analysis of capability and the limits of the software reviewed above leads us to choose **MoorDyn** as the best mooring solver to compute the hydrodynamic analysis suited to the research purpose. The principal reasons are explained in the following:

- A consolidated knowledge of the MoorDyn environment, Matlab/Simulink.
- MoorDyn could be implemented with an already existent ISWEC model developed in the Simulink working space.
- An extensive use of MoorDyn in several pieces of research testified by a large bibliography [20] [21] [22] involves experimental scale model data or validation test against other commercial software (i.e. Orcaflex). Despite the differences are not so marked, MoorDyn represents a good starting point for an early stage mooring system development.
- MoorDyn is an OpenSource software.

Base on the reported criteria, also **Moody** can represent a suitable option, but it was supported only in Macintosh or Linux Operating Systems, until recently.
MoorDyn is a lumped-mass mooring solver. The version considered in this paper is **v1.00.03C**, but some considerations regard the last version **v1.01.01C** which contains a beta model for seabed horizontal friction.
The MoorDyn design cycle is composed by three phases:

1) Quasi-static phase which identifies the position of each node from an input text file.
2) A dynamic relaxation phase, which defines the Initial Conditions (IC).
3) Mooring forces calculation and outputs are stored at each time step. An example of the desired outputs can be the tension of each fair-lead and the nodes' position.

In addition it is necessary considering that during the running of MoorDyn, some stability problems can occur due to the behaviour of the Damping coefficient and the Bottom stiffness.
Acting properly on the Input file it is possible to avoid these instabilities and build an effective model. In particular to ensure the correct **damping coefficient** it is possible to use the critical damping ratio in the already exposed MoorDyn versions. Of course the damping is only a mathematical method to avoid numerical instability especially talking of chain lines. For the paper's purposes, a damping ratio of 0.1 has been considered.
Quasi-static phase
During the building of the model in Quasi-static phase, MoorDyn identifies the position of each node starting from the .txt file. However, the input positions can be too far from the IC, obtained by the Dynamic Relaxation process, to fix this issue

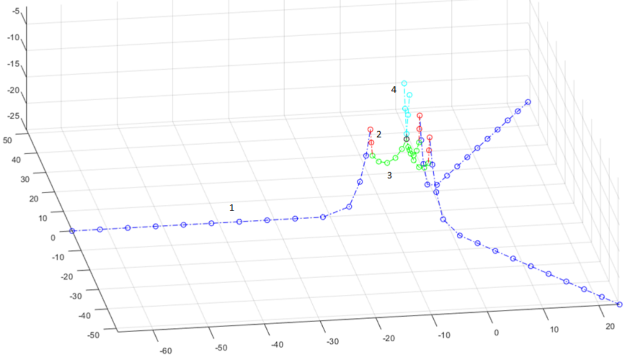

Fig. 2. Mooring System C2a Configuration

MoorDyn generates automatically nodes between the line connectors and uses them to compute the IC position. This process brings to an instability problem which gives NaN as result. To overcome this issue, the model has to be structured changing the coordinates of the intermediate connection points not casually but allowing to find at the system the IC condition during the dynamic relaxation.

Dynamic Relaxation

The quasi-static phase is followed by the dynamic relaxation which ensures to find the initial condition for the system nodes. The IC can be affected by the starting position of the nodes and a ramp function could be used to ensure a better transition phase and avoid instability. Another strategy is represented by the changing of the IC incremented damping from the input file, which ensures a slower nodes motion between starting position and equilibrium position.

During running

At last, the time step chosen can affect the stability of the simulation, or a wrong integration time set in the input file can create problems too. This debug step is remarkably sensitive to the strong connection between parameters, for example, integration time and spatial discretization.

Other information

In the new version **v1.01.01C**, there is a beta model for horizontal seabed friction with static friction and Columbian model friction.

VI. MOORING SYSTEM

After having explained the system simulation procedure with the use of MoorDyn software and the challenges of the numerical models, two different mooring system configurations designed for ISWEC are presented. The systems are thought to be experimentally tested in the naval tank of the Univesità Federico II, in Naples. The configurations tested during the experimental campaign are called C2A and C1 as shown in Figures 2 3. Both configurations are formed by three catenary bottom lines anchored to the seabed (in blue in figures), at the end of them there are three jumpers. In C2a configuration jumpers are connected to the clump-weights which in turn are connected to a rotating joint. From the swivel, the bridles connect the joint to the hull. In C1 configuration instead there are no clump-weights and the jumpers are directly connected to the swivel. Both tested configuration have a loadcell which ensures to store tension data. The loadcell is located between the swivel and the bridles.

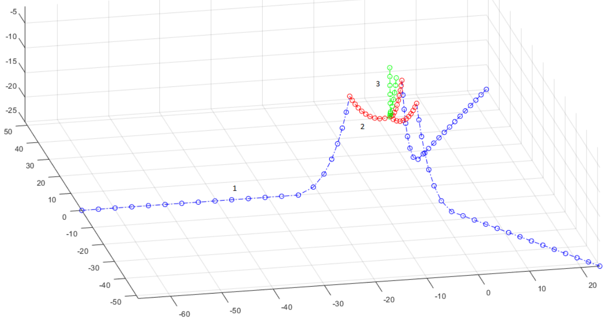

Fig. 3. Mooring System C1 Configuration

TABLE IV
CATENARY LENGTH C2A

Line	Line Type	Unstretched Length [m]
1	Catenary B	65
2	Catenary B	5
3	Catenary B	10
4	Catenary T	9

TABLE V
CATENARY LENGTH C1

Line	Line Type	Unstretched Length [m]
1	Catenary B	65
2	Catenary B	10
3	Catenary T	9

Mooring system models created in MoorDyn have been made up-scaling the model tested in Naples. Mooring system lengths are reported in Table IV for C2a configuration and in Table V for C1 configuration. In Table VI is possible to observe the chains properties which have been used in this mooring system, particularly one used only for the top connection between swivel and fair-leads, and the other chain used for the remaining part of the lines.The remaining properties of the mooring have been reported in Table IV. The scaled mooring tested during the experimental campaign has been built with a load cell to store the tension signal. The load cell in the up-scaled model built in MoorDyn has been modeled as a catenary segment (in black in the figure 2).

In Table (VII) there are jumpers and clump-Weights properties.

VII. SIMULATION PROCESS

All the simulations were made with full-scale model, therefore prototype's motion was up-scaled with Froude.

TABLE VI
CATENARY PROPERTIES

Catenary Type	EA[N]	weight[kg/m]	d[m]
Catenary B	3.24E8	74.4	0.114
Catenary T	1.74E7	36	0.084

TABLE VII
JUMPERS AND WEIGHTS PROPERTIES

	Net Weight[kg]
Jumpers C2a	3587
Jumpers C1	1512
Weights	2000

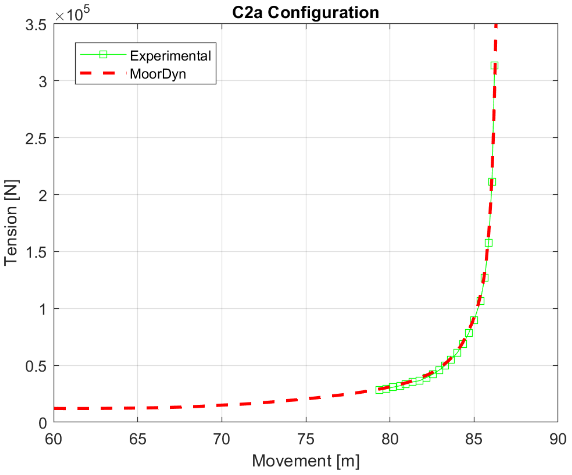

Fig. 4. Static Validation C2a

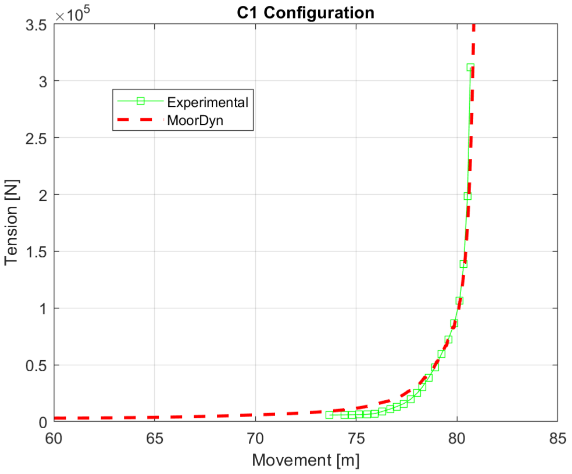

Fig. 5. Static Validation C1

A. *Load-excursion curves: Validation*

The first step is to obtain the validation of the model considered through a load-excursion curves. This validation consist of giving motion in x-direction (surge) and storing the mooring tension. Firstly C2a configuration is presented (fig. 4).

The model shows a good match with experimental data. There is a perfect match with vertical asymptotic curve, which is mainly governed by mooring length and lines axial stiffness, and also a good math with horizontal one, which is governed instead by the static load (restoring force due to line weight). The differences between horizontal asymptotes can be caused by seabed friction, but a perfect modeling of the phenomena could be difficult to obtain from experimental tests where the wave tank seabed friction coefficients are difficult to estimates. This is why differences between horizontal asymptotes in C1 static test exist, 5 but the match is very good with vertical one.

B. *Dynamic Validation*

MoorDyn validation process follows with the validation of experimental data in irregular wave. Of course, MoorDyn is only a mooring solver, hence it cannot solve the system hydrodynamics, and motions shall be imposed.

During the experimental campaign, several waves were tested, but for some technical problems related to the load cell, with only 2 waves a good tension time history has been recorded. Table VIII shows the properties of the waves tested.

As said previously, the whole validation process is focused on the comparison between the line's tensions recorded through a load cell and the same tensions obtained by MoorDyn. Also in this section, the validation process follows the same theme.

The results are very good for C2a configuration (Figure 7). Model follows the tension trend properly and overlaps experimental tension. Instead for C1 configuration model, numerical model tension follows the experimental tension properly but the snap events are quite difficult to be modelled. Several uncertainties could lead to a bad modeling of these events, and for the difficulty to exstimate the axial stiffness of the lines. In Table IX are exposed the results in terms of standard deviation variation and mean value variation, where:

$$\Delta_\mu = 100 * \frac{\mu_{MoorDyn}-\mu_{exp}}{\mu_{exp}}.$$
$$\Delta_\sigma = 100 * \frac{\sigma_{MoorDyn}-\sigma_{exp}}{\sigma_{exp}}.$$

VIII. CONCLUSION

A mooring system model is really important in the WEC dynamic and withstanding capability. For this reason a review analysis of the available models and software has been carried on and MoorDyn has been chosen as the best software to pursue the study purpose. The choice mainly regards the MoorDyn availability online for free, and its versatility thanks to the Matlab interface. The capability of the software is

TABLE VIII
TESTED WAVE PROPERTIES

Variable	Unit	C1 configuration	C2a Configuration
Energetic period, Te	s	5.14	5.05
Peak period, Tp	s	5.41	5.41
Significant Wave Height, Hs	m	2.02	2.08

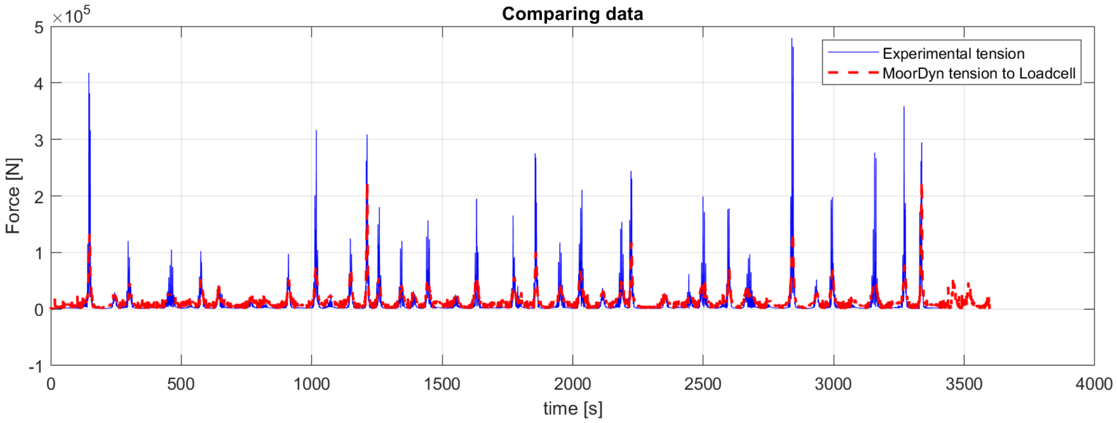

Fig. 6. Kinematic Validation C1

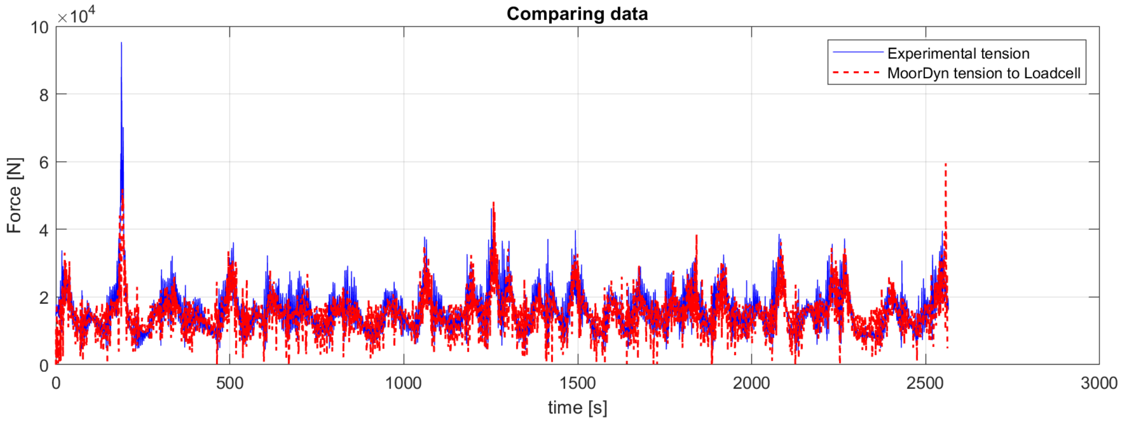

Fig. 7. Kinematic Validation C2A

TABLE IX
RESULTS

Configuration	Δ_{μ}	Δ_{σ}
C2a	6.65	10.3
C1	52.6	29.5

tested in comparison with experimental data obtained during the experimental campaign performed in the wave tank at ”Università di Napoli Federico II”.

The MoorDyn capability are very promising, and its capability to model snap events (which should be investigated in last details) could not be a problem in operative conditions.

For this reason, it can be claimed that both goals have been reached, on one hand, a compendium of the mooring design software has been reported, highlighting the key points and the theoretical methods considered, on the other hand, the MoorDyn validation has been presented, as shown in fig.6 and fig.7.

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