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Design of a 6-DoF Robotic Platform for Wind Tunnel Tests of Floating Wind Turbines

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Abstract

Sophisticated computational aero-hydro-elastic tools are being developed for simulating the dynamics of Floating Offshore Wind Turbines (FOWTs). The reliabilty of such prediction tools for designers requires experimental validation. To this end, due to the lack of a large amount of full scale data available, scale tests represent a remarkable tool. Moreover, due to the combined aerodynamic and hydrodynamic contributions to the dynamics of FOWTs, experimental tests should take into account both. This paper presents the design process of a 6-Degrees-of-Freedom robot for simulating the dynamics of FOWTs in wind tunnel scale experiments, as a complementary approach with respect to ocean wind-wave basin scale tests. Extreme events were considered for the definition of the robot requirements and performance. A general overview on the possible design solutions is reported, then the machine architecture as well as the kinematic and dynamic analysis is discussed. Also a motion task related to a 5-MW Floating Offshore Wind Turbine nominal operating condition was considered and then the ability of the robot to reproduce such motions verified in terms of maximum displacements, forces and power, to be within the design boundaries.

Keywords: Floating Offshore Wind Turbines ; Aero-hydro-elasticity; Wind Tunnel; Wind Energy; Hardware-in-the-loop; Hexapod; Hexaglide.

1. Introduction

Offshore Wind Energy is playing a significant role in facing the worldwide energy demand. In this scenario, the development of Floating Offshore Wind Turbines (FOWTs) represents a new challenge for both academia and industry, for their complexity in the design process, long-term reliability and performance assessment, investments, operations and management [1]. Nevertheless, deepwater multi-megawatt installations and strong wind resources make these challenges attractive. In the last decade, sophisticated codes have been developed to compute the coupled aerodynamics and hydrodynamics of FOWTs. Among others, the open-source aero-servo-elastic code FAST (Fatigue, Aerodynamics, Structures and Turbulence) has been developed by Jonkman J. at NREL ([2], [3]), and integrated with the hydrodynamics of the platform and mooring dynamics, by means of the module HydroDyn. More specifically, HydroDyn is able to include in FAST the frequency-dependent added mass and damping matrices and wave exciting

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forces, coming from the solution of the first-order potential problem (e.g from WAMIT [4]), as well as hydrostatic restoring matrix and viscous-drag forces. Therefore, the global aero-hydro dynamic model is solved by FAST, for a given sea-state (i.e Pierson-Moskovitz, Jonswap spectra), giving the possibility to simulate specific load-cases, as required by the current offshore structures standards [5].

Motivation and objectives. The sophistication of such codes, as well as the limited availability of full scale data, brings about the need of experimental campaigns for validation. First of all, the validation process requires scale test experiments, where the number of varying input parameters are reduced, controlled and correlated with the measured output. Recently scale tests of FOWTs were performed in various water basins. Remarkable results come from tests carried at Maritime Research Institute Nederlands (MARIN) where, under DeepCWind consortium [6], the global dynamic response associated to different platforms (spar, semi-summersible, tension-leg) and for different only-wave or wind-wave conditions was studied. Such tests reported the importance of developing and validating codes that combine the aerodynamics and hydrodynamics of FOWTs, tightly coupled in terms of the frequency content (i.e the second-order difference-frequency hydrodynamics and turbulence on a semisubmersible FOWT [7]). The aim of this work is to propose a complementary approach to test scale models of FOWTs [8]: more specifically, the design of a 6 degrees-of-freedom (DoF) robot, "HexaFloat", capable of reproducing the floating motion of a scale FOWT for wind tunnel experiments, is herein reported and discussed. This approach allows to investigate more thoroughly the aerodynamics of FOWTs due to different wind- and sea-states, relying on aeroelastic FOWT scale models (possibly individual pitch controlled) and the 14m×4m civil boundary layer test section of Politecnico di Milano [10], whose 35m long and constant section allows to passively or actively generate short and long turbulence length-scale (turbulence index $< 2\%$ and $> 25\%$). Therefore, the target of this work is creating a tool for better understanding the effect of hydrodynamics on the aerodynamics of FOWTs and then for validating the above mentioned aero-servo-hydro-elastic codes and giving new perspectives on the modeling of FOWTs aerodynamics, as well as pitch control strategies. Nowadays, the international effort put into the verification and experimental validation of Computer Aided Design (CAD) tools for FOWTs is remarkable. In this regards, the International Energy Agency IEA, under the coordination of National Renewable Energy Laboratory NREL, set up the Offshore Code Comparison Collaboration Continuation (OC3-OC4) [9], with the aim of sharing expertise and performing load-case benchmark excerices on FOWTs models as well as carrying out experimental validation of such codes, among various institutions, facilities and industrial partners. These collaborations have been recently extended to the OC5. From this perspective, wind tunnel tests, by means of the device presented, can play a useful role to integrate the experimental evidence emerged from scale tests carried out so far in wind-wave ocean basins. To this purpose, this work presents a customized design process of a 6-DoF robot Fig.1, for this specific application, having ability of functioning in two different configurations: providing given motion laws along single or coupled degrees of freedom or by hardware-in-the-loop mode, where motion is given in real-time consistently with the aerodynamics (measured) and hydrodynamics (computed), as extensively explained in [8].

2. Robot requirements

In order to define the requirements and the specifications for the design process of HexaFloat, in terms of maximal displacements and frequencies of the robot mobile platform, the FAST simulations by Jonkman J. [11] of three different floating platform concepts (MIT/NREL TLP, ITI Energy Barge, OC3-Hywind) were considered as reference. More specifically the worst cases of the FAST output related to the platform displacements *PtfmSurge, PtfmSway, PtfmHeave, PtfmRoll, PtfmPitch, PifmYaw* were considered. Therefore the displacement $d = (disp_{max} - disp_{min})/2$ was taken into account as extreme displacement from the nominal position and then scaled following Froude-scaling approach, with a scale length factor $\lambda_L = 1/58$, with respect to the 5MW-NREL wind turbine [12], that is compatible with the dimensions of the Politecnico di Milano wind tunnel test section [10]. Similarly, the maximum platform accelerations *PtfmTAxt, PtfmTAyt, PtfmAzt*, scaled by a factor $\lambda_a = 1$ were considered to define the maximal frequencies, assuming pure sine translations of amplitudes d. In regards to the scaling approach, the major challenge is overcoming the inability to maintain simultaneously Froude and Reynolds numbers for a scaled floating wind turbine experiments. In wind tunnel testing Reynolds number scaling is commonly used to establish model parameters in order to properly represent the relationship of viscous and inertial forces for a fluid flow, whereas in wave basin testing Froude number similitude is typically employed to properly scale the gravitational and inertial properties of wave forces, which are the

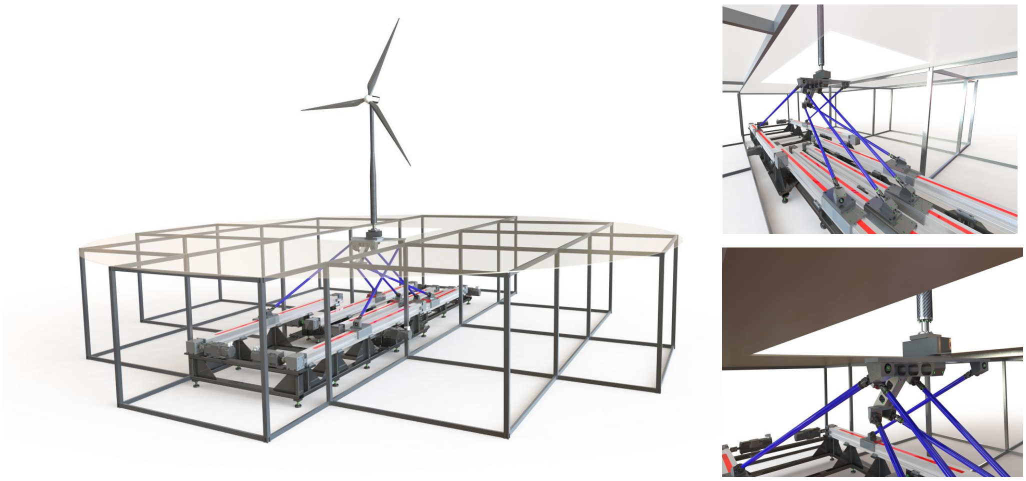

Fig. 1: 6-DoF Robotic Platform “HexaFloat” for wind tunnel tests of FOWTs.

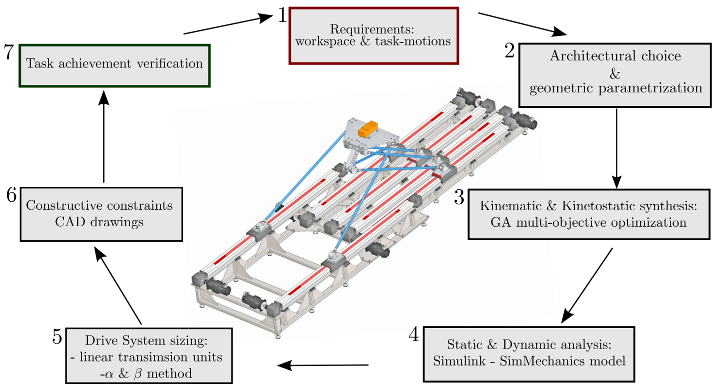

Fig. 2: Design flow-chart.

dominant external forces for a floating vessel or structure. Although the scaling process for testing FOWTs requires specific considerations, as reported in [13], in order to define only the extreme HexaFloat specifications, Froude-number similitude, as performed in [6] and [7], in relation to extreme events of [11], was considered compatible with the purpose of this work. Furthermore, Froude scaling approach seems to be mandatory for this specific application in order to be able to compare the results with the water-basin counterpart tests. Moreover, these extreme requirements have been increased in order to meet also the specifications due to possible more demanding scale factors, in terms of scaled frequency, and to make sure to be able to cover the whole scaled wave energy frequency range, assuming a full-scale wave cut-off frequency of $\omega = 3$ rad/s (for greater frequencies the wave energy, as well as the response of the floating systems, can be considered negligible, in relation to first order and second order/sum-frequency hydrodynamics [7]). Therefore, for these reasons, HexaFloat was designed for a set of extreme specifications and verified also for a set of greatly higher frequencies and lower displacements, as shown in Tab.1.

3. Robot design process

Given the specifications mentioned above (Tab.1), the final features and performance were reached through a multi-objective iterative process as reported in Fig.2, dealing with technical constraints as well as general assessments, that typically affect the design of a complex machine. The HexaFloat design process can be summarized by the following

	Design		Verification	
Dof	[m]	[Hz]	[m]	[Hz]
Surge	0.5	0.7	0.01	3
Sway	0.3	0.7	0.01	3
Heave	0.25	0.7	0.01	3
	[deg]	[Hz]	[deg]	[Hz]
Roll	15	0.7	3	3
Pitch	15	0.7	3	3
Yaw	15	0.7	3	3

Tab. 1: HexaFloat requirements.

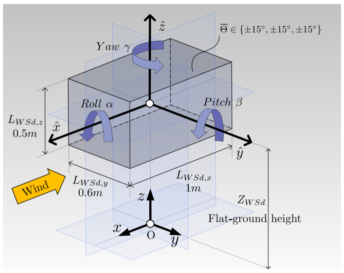

Fig. 3: Desired workspace.

steps: (1) definition of a total orientation workspace, accordingly with the preliminary requirements; (2) choice of machine architecture and related geometrical parametrization; (3) kinematic synthesis by multi-objective optimization of the machine dimensions, by means of a genetic algorithm (Pareto optimality); (4) definition of the "best" solution by means of static and dynamic analysis of the Pareto-optimal solutions; (5) mechanical sizing of the drive system and other mechanical equipments.

Machine architecture. The family of "parallel kinematic" robots (PKM) was chosen for its more suitable capabilities, compared to serial robots. The main peculiarities of such robots can be defined as follows: (1) *High positioning accuracy*: there are different sources of error that affect the positioning accuracy of a robot, such as the backlash in the joints, the sensors accuracy, the deformations of the linkages, the assembly errors as well as the geometric errors due to the manufacturing tolerances. In serial robots, errors and backlash are summed together amplifying their effect upon the end-effector positioning, whereas in parallel robots, errors and backlash interact in a more complex manner, averaging. Therefore the positive effect is a lower overall sensitivity of the end-effector positioning to the various sources of error, whereas the negative is that an error related even to a single element of the kinematic chain affects all of the end-effector DoF, so that these errors can be hardly isolated and corrected. (2) *High load capability*: parallel robots usually have great stiffness and the capacity of discharging heavy loads to the ground efficiently, ensuring a high ratio between the payload mass and their own mobile mass. The structure of such machine is kinematically defined by closed loop chains, so that loads tend to be equally distributed through the linkages and mainly lengthwise to the linkages (highest stiffness and then smallest deformation and positioning error). (3) *High dynamic performances*: the actuators are mounted close to the base or directly placed to the ground, minimizing the mobile mass of the robot and allowing high speed motions. Due to the closed loop chains, the dynamic loads tend to be equally distributed on the various links, so that the actuators can be chosen of the same size. (4) *Components modularity*: this aspect makes the design process faster and cheaper, as well as the off-line reconfiguration and transportation of the items, easier. A remarkable outcome of the modularity of the components is the possibility of easily reconfigure the machine due to changes in the specifications, that makes this robot eligible of design modifications for specific testing requirements. For these reasons, PKM was chosen to simulate the floating motion of scale FOWTs, although the design process more complex and not pre-defined with respect to the industrial serial robots. However, this type of robots, has been adopted in the last decades for motion simulators, vibrating tables, positioning and pointing systems. Accordingly, due to the strong dependency of the performance of a PKM robot on its kinematic topology and its dimensions (Merlet J.P. [14], Weck M. & Staimer D. [15], Legnani G. [16] and Giberti H. [17]), a multi-objective task-oriented customization was necessary to meet the specification of Tab.1.

From literature, a considerable number of 6-DoF PKMs are proposed. However, as indicated by Bonev I.A. [20], such robots can be reduced to a limited number of kinematic topologies, although their implementation can be performed by means of a potentially infinite number of variations. This work refers to the so called "Hexaglide" kinematic architecture, also known as 6-$\underline{P}$US (Prismatic Universal Spherical) architecture with parallel rails. It is characterized by six links of fixed length, that connect the base to the mobile platform (where the scale model of the floating wind turbine is supposed to be placed), and its motion is given by the actuation of six prismatic joints, that lay parallely to the base. This structure has the following advantages: (1) low workspace center (Tool Center Point) TCP: for this specific application, having a very low TCP is a mandatory requirement in order to leave as much free space to the model as possible within the wind tunnel test section [10], in order to avoid that the model enters the boundary

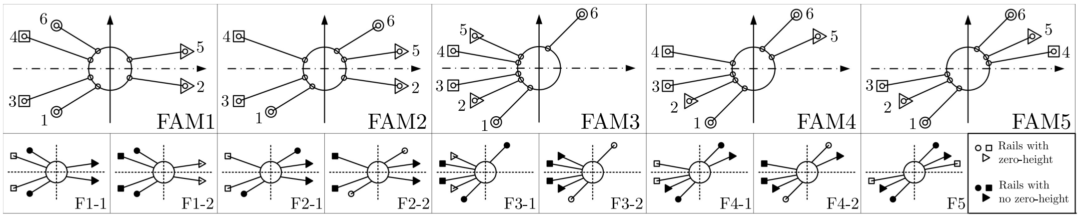

Fig. 4: Simmetric architectural families.

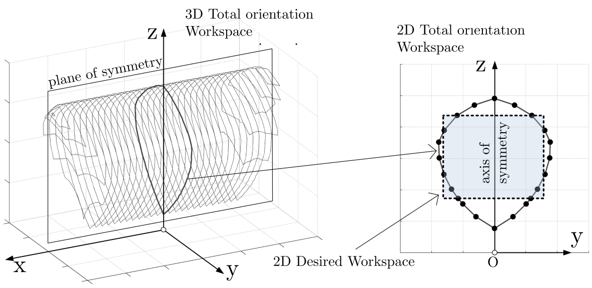

Fig. 5: Simmetric total orientation workspace: from 3D to 2D.

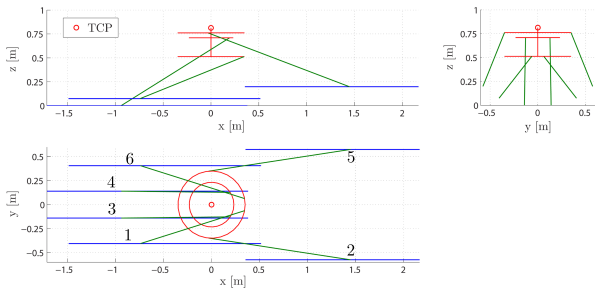

Fig. 6: HexaFloat links disposition (FAM1-1, Fig.4).

layer at the top of the section, inevitably affecting the measurements. This means bigger models, less scaling effects and less blockage effect of the wind tunnel tests. Also the parking position is low. (2) the workspace is characterized by a predominant direction that can coincide with the direction of the wind, along which the maximum amplitude of the robot movement is required to simulate the surge motion of the model. (3) the actuation is placed completely on the ground, so that a good ratio between the payload mass and the mobile mass of the robot is ensured, allowing high dynamic performances and slender links, reducing problems of interference.

This solution was firstly adopted at ETH of Zürich [18,19] and later discussed by Bonev I.A. [20] and others [21–25]. Recently it was applied at the NWB-DNW wind tunnel in Braunshweig (Germany), named *Model Positioning Mechanism* [26,27]. All these examples refer to custom-made PKM not commercially available, for the same reasons explained.

Geometric Parametrization. The Hexaglide robot is characterized by fixed links and parallel rails, that are not necessarily coplanar. All the other architectural details are determined through a geometric parametrization, which is performed consistently with the requirement of a symmetric total orientation workspace with respect to a vertical plane, parallel to the rails and passing through the longitudinal centerline of the machine, as shown in Fig. 5. To this aim, assuming the mobile platform in its zero-oriented attitude and the TCP in the workspace center, the links in pairs must be in accordance with one of the following two criteria of symmetry: (1) symmetry with respect to the vertical-longitudinal plane, or (2) the central symmetry with respect to the vertical axis passing through the TCP. As show in Fig. 4, the parametrization leads to a lot of different architectural families. Moreover, since the rails are arranged parallel to each other, the boundary of the workspace can be evaluated over a single *yz*-plane perpendicular to their direction, simplifying the problem from 3D to 2D, Fig. 5.

Kinematic Synthesis. The parametrized dimensions of the manipulator are then determined by means of a multi-objective optimization campaign, performed by genetic algorithm [28], implemented by the Matlab function `gamultiobj.m`. The objectives to be achieved by this analysis deal with: (1) the coverage of the workspace, (2) the static forces multiplication, (3) the interference between the links, (4) the interference between the links and the rails, and (5) the longitudinal size. To achieve these objectives, two appropriate cost functions were considered, as explained in [29]. Also, in order to decrease the computational effort, the objectives (1-4) were considered as once by defining appropriate thresholds, in terms of maximal static force multiplication and minimal link-to-link and link-to-rail distance allowed, so that only if these thresholds were not exceeded, the corresponding robot pose (TCP position and platform orientation) was considered acceptable, as well as the related set of geometric parameters to be

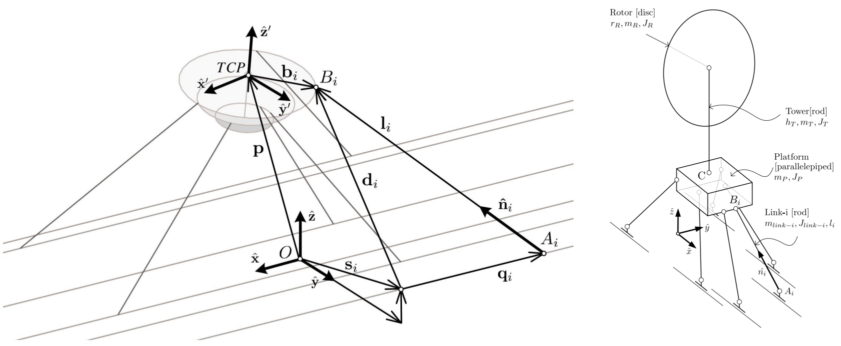

Fig. 7: HexaFloat kinematics and dynamics sketches.

Symbol	Units	Values
m_P	[kg]	35
m_{link}	[kg]	1.5
m_T	[kg]	7.0
h_T	[m]	1.70
m_R	[kg]	3.0
r_R	[m]	1.0
l_{link1}/l_{link6}	[m]/[m]	1.22
l_{link2}/l_{link5}	[m]/[m]	1.60
l_{link3}/l_{link4}	[m]/[m]	1.34

Tab. 2: Inertial and geometrical properties.

optimized. After the convergence of the iterative process, different Pareto-optimal solutions were obtained and then kineto-statically analysed and compared.

Dynamic analysis. The inverse dynamics of the robot was solved by a multi-body model developed in Simulink, relying on SimMechanics library. At this stage, the inertial properties were considered of simple rigid bodies, as shown in Fig. 7. The inertial values are reported in Tab. 2. The links are modelled as rods with length l_i, whereas the platform as a parallelepiped of a minimal size, containing the TCP and all the centers B_i of the S-joints therein connected. Therefore, given zero-mean sinusoidal motions of each degree of freedom and solving the inverse dynamics, the forces on the links, responsible of such motions, were computed. Moreover, in order to cover the whole workspace, the inverse dynamics was computed for every sub-workspace in which the total orientation workspace was discretized, considering every center of such sub-workspaces as nominal TCP position and platform orientation. This procedure allowed to define the related maps of the forces components, linear velocities and accelerations for the whole workspace [29]. This was useful to compare different Pareto-optimal solutions, considering also other technical issues such as mounting, management and cost-effective aspects. At this point, the best compromise solution was chosen and then verified, as reported in Fig.2. In regards to the system actuation, two possible different technologies were taken into account and compared: screw-driven units and belt-driven units. Considerations of these two types are extensively reported in [29]. New distribution maps were produced using the “alpha” and “beta” theory for selecting the motor-reducer unit, as reported in [30]. Eventually, the links were sized for yielding and buckling resistance.

The robot kinematic design was carried out with reference to [29,31], where the adopted methods and analyitical formulations are discussed in detail. In the Fig.8 the main components of HexaFloat are reported. Among others, the spherical joint required to be customly designed in order to allow the great mobility searched for HexaFloat.

4. Simulation tool and results

A Simulink/SimMechanics rigid multibody model was developed as a prediction tool for defining and sizing the HexaFloat actuation system Fig.8 in regards to the extreme-events requirements of Tab. 1. Nevertheless such a tool was developed with the aim of verifying off-line the performance of HexaFloat for a specific task also involving the contemporary motion of all 6-DoFs, although the design process relied on single-DoF sine motions of specific amplitudes and frequencies (Tab. 1), or considering different payloads than the ones specified in Tab.2, due to different FOWT scale models. This tool gives the possibility to simulate the consistency of the dynamics, due to the requested task, and the motion that HexaFloat is able to provide, as well as the maximum forces required. For the sake of completeness, a specific input task was considered (Fig. 9) and the results in terms of slider displacements are reported in Fig. 10, whereas Fig. 11 and Fig. 12 show respectively the reactions forces on the slider for each link and the axial forces on the links themselves. Comparing these results to the maximum values allowed by HexaFloat (Fig. 13) it can be noted that laying the design process on extreme events was useful to make HexaFloat able to reproduce nominal FOWT operating conditions for a consistent scale factor. More specifically, FAST simulation of the full scale OC3 system was performed considering the nominal operational condition with a sea-state given by Jonswap spectrum with

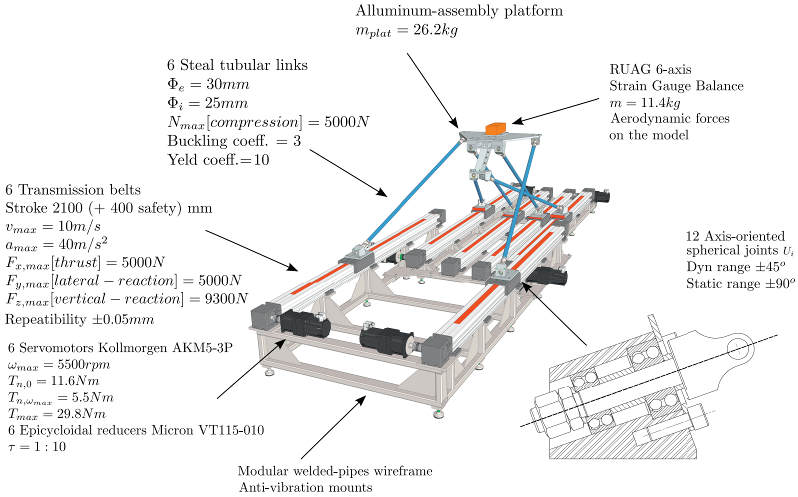

Fig. 8: HexaFloat main components.

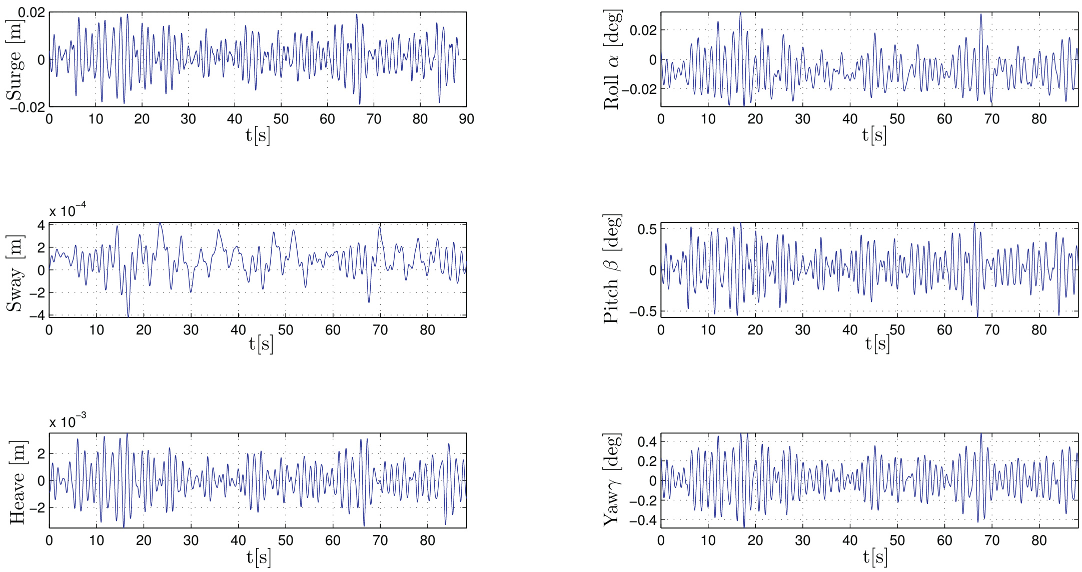

Fig. 9: OC3-Hywind 1/58th Froude-scaled displacements.

wave height $H_s = 3.66$ m and pick-period $T_p = 9.7$ s, constant wind speed $V = 11.4$ m/s, rotor speed $\omega = 12.1$ rpm. The output displacements of the platform (Surge, Sway, Heave) were Froude-scaled with the above mentioned scale factore $\lambda_l = 1/58$ and the time axis scaled by the factor $\lambda_t = \sqrt{\lambda_l}$, the rotations amplitude (Roll, Pitch, Yaw) were not scaled. The scaled time histories of Fig. 9 were mean subtracted from FAST output. Firstly, the inverse kinematics was solved, Fig. 10 shows the slider displacements q_i that represent the control variables as well; infact, for each of closed kinematic chain represented by the links (Fig.6 and Fig.7) it is possible to define the following equation for the length of the link l_i:

$$l_i^2 = \mathbf{l}_i^T \mathbf{l}_i = (\mathbf{d}_i - \mathbf{q}_i)^T (\mathbf{d}_i - \mathbf{q}_i) = \mathbf{d}_i^T \mathbf{d}_i - 2\mathbf{d}_i^T \mathbf{q}_i + \mathbf{q}_i^T \mathbf{q}_i \tag{1}$$

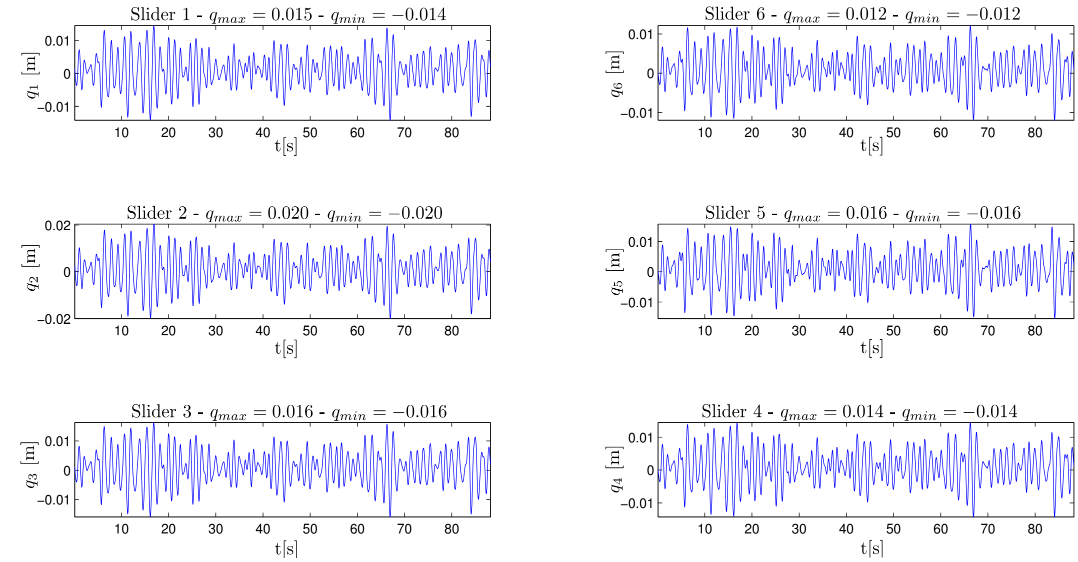

Fig. 10: HexaFloat slider displacements for the task considered.

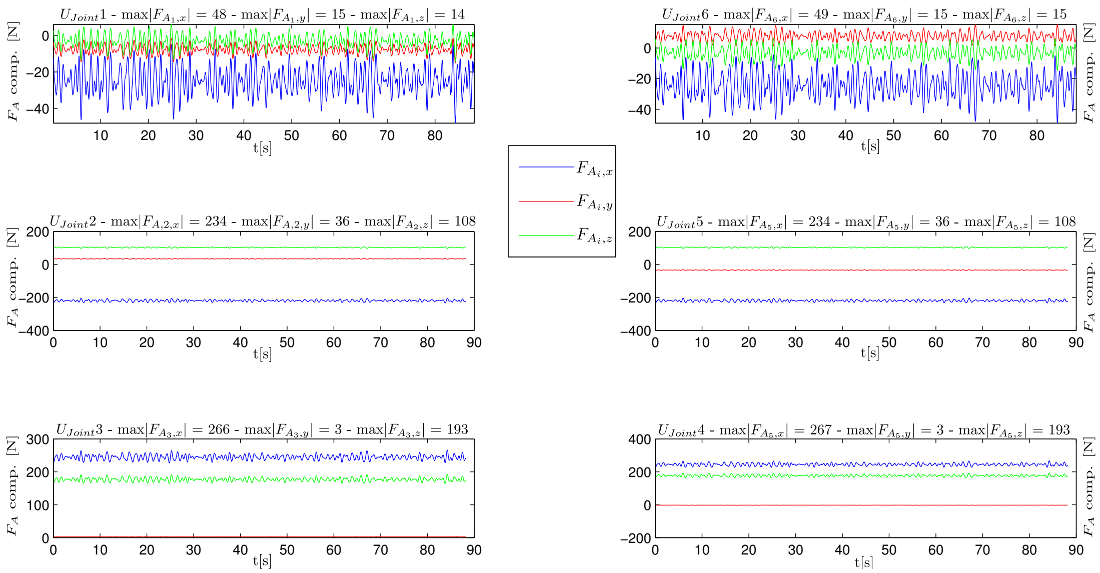

Fig. 11: Reaction forces on the sliders for the task considered.

where $\mathbf{d}_i = \mathbf{p}_{TCP} + [R]\mathbf{b}'_i - \mathbf{s}_i$, $\mathbf{q}_i = q_i\hat{\mathbf{x}}$ and $[R]$ is the rotation matrix, as function of the platform trim. Therefore, after appropriate manipulations, a second-order equation is obtained as function of unknown q_i, whose solution is:

$$q_i = d_{i,x} + h_i \sqrt{l_i^2 - d_{i,y}^2 - d_{i,z}^2} \tag{2}$$

with $h_i = +1$ or $h_i = -1$ depending on the assembly [29]. More specifically, each robotic architectural family depicted in the Fig. 4 is carachterized by a specific assembly and then by a consistent vector $\mathbf{h} = h_1, ...h_6$, where h_i is positive or negative depending on the disposition along the axis x. HexaFloat belongs to the Fam. 1-1 of Fig. 4. Secondly, by performing the multibody analysis, the forces and torques of the links are computed and verified to be within the

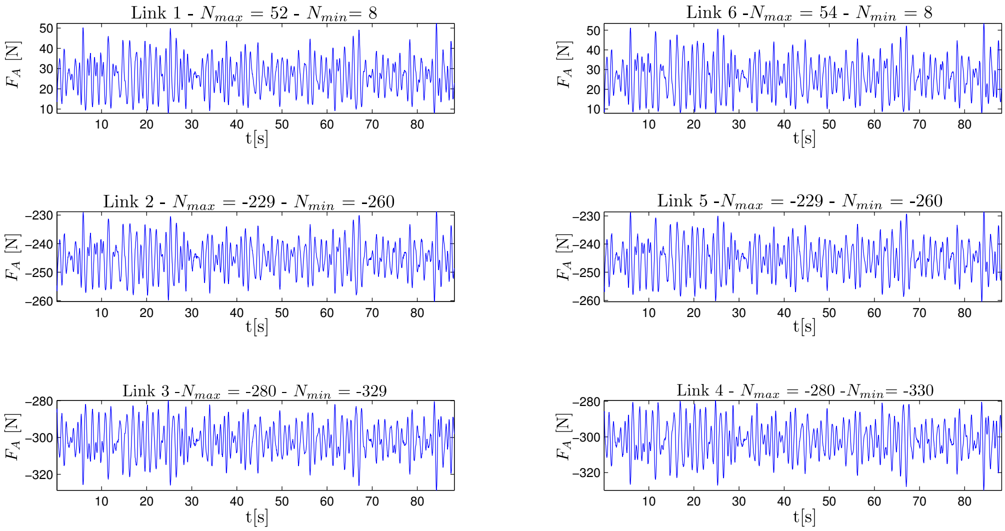

Fig. 12: Axial forces on the links for the task considered.

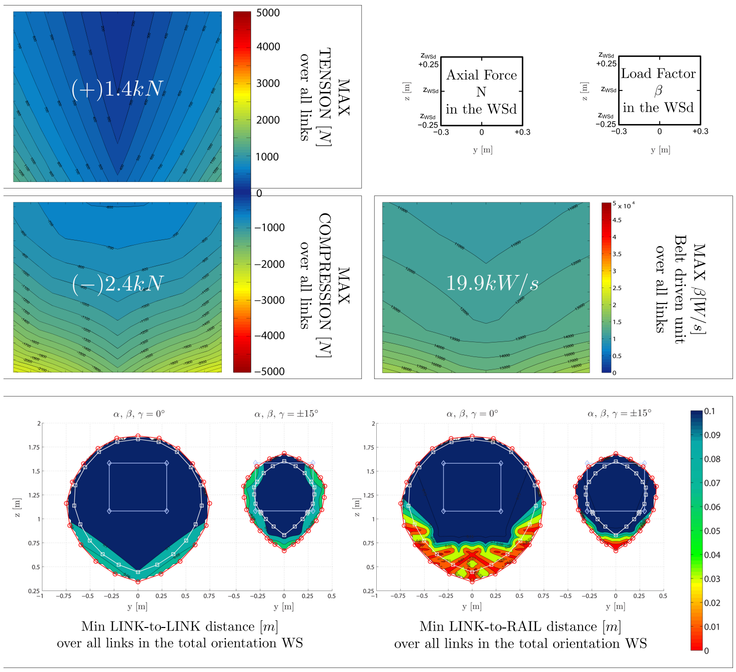

Fig. 13: HexaFloat capabilities summarized into maps.

given design constraints (as reported in Fig. 13), as well as the motor-reducers performance requested by following the procedures reported in [30] and [31].

5. Conclusions

The design process of “HexaFloat”, a 6-Degrees-of-Freedom PKM-Hexaglide robot for simulating the dynamics of Floating Offshore Wind Turbines (FOWTs) in wind tunnel scale tests, was reported. The motivation of this work lays on the need of validating, by means of scale test experiments, sophisticated aero-hydro-elastic simulation tools as well as control strategies and to provide a complementary approach with respect to water basin scale tests, with a greater attention to the influence of the floating motion on the aerodynamics. The design process of “HexaFloat” was carried out starting from the definition of the requirements due to extreme sea-state and the related dynamics of three different platform concepts combined with the 5-MW reference FOWT (NREL). Due to the peculiarity of the task, the design of the robot was carried by means of a multi-objective optimization which considers the coverage of the workspace, the static forces multiplication, the link-to-link interference, the link-to-rail interference, and the longitudinal size. A rigid multibody model was developed for assessing the dynamics of HexaFloat due specific motion-tasks and for sizing the actuation system. The scaled motions of a 5-MW spar buoy FOWT were analyzed as reference case to verify the reliability of the robot to reproduce the dynamics of nominal operating conditions, in terms of slider displacements, forces and power within the design ranges.

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