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Experimental Investigation of a Novel Concept of Modular Multi-Purpose Floating Structures

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Abstract. Modular Multi-purpose Floating Structures (MMFS) provide a possible solution to the growing need for space resulting not only from the rapidly growing global population but also from the expanding blue economy sector. The desired space is generated in a more sustainable way than land reclamations methods, by interconnecting together standardized floating modules, making this technology adaptable and suited to a broad range of possible open sea application. Herein, this study aims to investigate the dynamical response of a system composed by three floating hexagonal modular platforms connected via semi-rigid connectors and moored at the seabed with a taut mooring configuration. An experimental investigation has been carried out on a 1:50 prototype at the wave basin of the Laboratory of Hydraulic Engineering (LIDR) of Università degli Studi di Bologna.
The objective of the paper is the experimental validation of the proposed technological concept, through the assessment of the loads acting on the system and the evaluation of comfort indices for various representative sea states. The preliminary results show the trends of the loads acting on the connection system and the mooring system, which are essential for the correct design of the full-scale system. Additionally, the comfort and safety indices are met for all the analyzed sea states, demonstrating the validity of the proposed design.

Keywords: Modular Multi-purpose Floating Structures, experimental campaign, mooring system, multi-body hydrodynamics, Very Large Floating Structures.

1 Introduction

In the blue economy sector, Very Large Floating Structures (VLFS) are an attractive way to potentially create space on water and sustain the blue economy activities. VLFS consist of floating modules that can be either rigidly interconnected or linked via semi-rigid connections and anchored to the seabed using a mooring system. For example, they can serve as logistics support bases for O&M operations and the installation of renewable offshore plants, facilitate aquaculture, seaweed farming, and vertical farming for countries facing land shortages, and help mitigate shipping traffic through the creation of floating port terminals [1]. Additionally, VLFS hold potential in the residential sector, offering a sustainable alternative to traditional land reclamation practices, which rely on environmentally harmful dredging techniques [2]. VLFS technology development has been primarily hindered by the high costs and technological limitations. The principal technical challenges involve the high loads acting on the structures and the harsh, corrosive marine environment [3], which significantly impact the comfort and usability of VLFS for the applications discussed above. In particular, two major VLFS's problems to be addressed are the reduction of hydro-elastic response of the system [4,5] and the high loads on the connection and mooring systems mainly due to waves action, both related to comfort and safety during operative and extreme events [6].

Within this context, this paper aims to describe a novel modular multi-purpose floating structure concept and the preliminary experimental results obtained on a scaled prototype. The new system concept is composed of interconnected floating modules linked to each other via semi-rigid connectors (which provide an optimum balance between the rigidity of the connections and the relative motion between platforms) and anchored to the seabed using a taut mooring, which provides better station keeping characteristics than catenaries. Additionally, the taut mooring system has a reduced impact on the marine ecosystem compared to catenary mooring, due to the absence of chains on the seabed and the consequent erosion and destruction of the seafloor. The main objective of this paper is to present the experimental campaign performed and the obtained outcomes, with a focus on analyzing comfort parameters for two configurations of the system (single platform and three "in line" floaters layout) in terms of maximum inclination, accelerations and loads acting on the mooring and connections.

2 Experimental Campaign Setup

The experimental campaign has been carried out in the wave basin of the Laboratory of Hydraulic Engineering (LIDR) of Università degli Studi di Bologna, illustrated in Fig. 1, whose dimensions are 12.00 (m) x 8.00 (m) x 0.60 (m) respectively in length, width, and water depth. Fig. 1 also describes the layout of the novel MMFS system under test, which consists of three hexagonal floating modules arranged in a line.

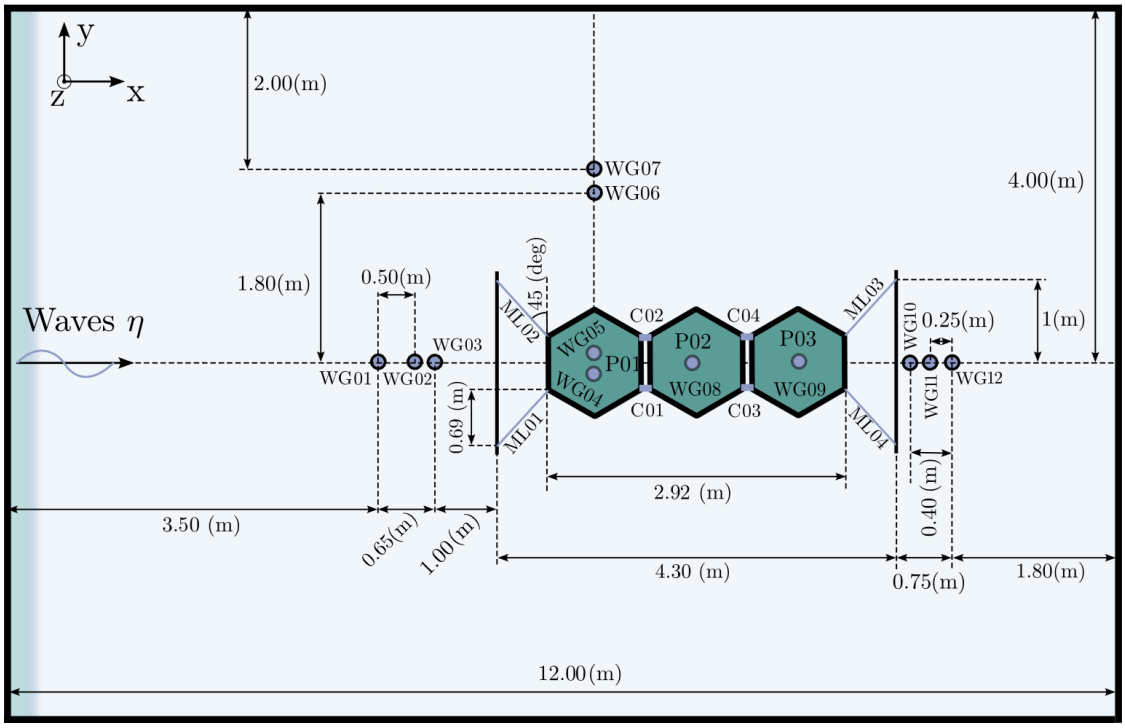


Fig. 1. Experimental setup of the LIDR wave basin facility. In the figure WG describes the position of the 12 wave gauges (shaded circles refers to WGs removed during the tests), ML refers to the four mooring lines, while C to the mechanical connectors between platforms. Figure adapted from [7].

Each module is made of stainless steel and appropriately ballasted internally, and it is shown in Fig. 2A. The semi-rigid mechanical connectors consists in mechanical piston The connection system consists of 5 mechanical pistons, which contain compression springs inside (see Fig. 2B and Fig. 2D). The mechanical pistons are connected to the ends of the structures through spherical joints to prevent shear forces and moments at the joints. The mooring line geometry is shown in Fig. 2C and has been realized using very stiff polyester ropes and an extension spring. Each mooring line and mechanical connector are equipped with a load cell.

For the present experimental tests, the connection system has been specifically designed to emulate the stiffness properties of the full-scale connector system, representing the axial, bending and shear stiffness of the system. A previous work concerning the analysis and optimization of the semi-rigid connector stiffness has been carried out [10]. During these experiments, both the isolated floater the three platforms in line layout has been tested. The Froude's law is used to scale the experimental design parameters from the full-scale to the prototype one (1:50), which are reported in Table 1. The system response is investigated under various regular and irregular sea states representative of moderately sheltered areas, and the complete test matrix is given in Table 2. Each sea state is generated with regard to the JONSWAP spectrum (peak enhancement factor $\gamma = 3.3$). The data acquisition system campaign consists in: a National Instruments C-RIO9042 module used to acquire signals from the load cells of the mooring and connector systems, a motion capture system (Qualisys) consisting in four cameras managed by a standalone PC, which starts recording after receiving a trigger signal from the C-RIO9042 module, and a separate data acquisition system handles the acquisition of the 12 wave gauges signals (WG01 to WG12).

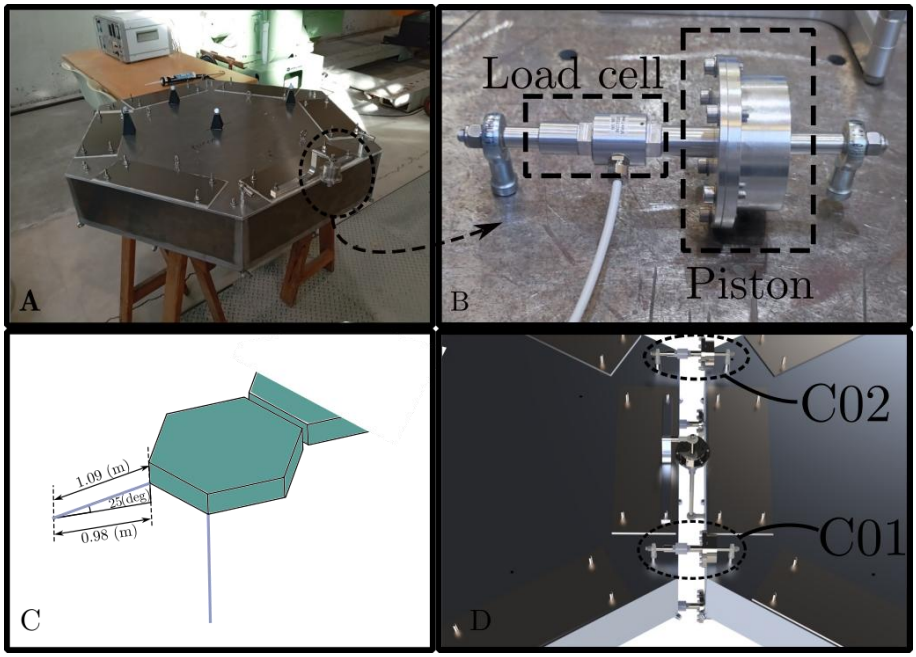


Fig. 2. MMFS tested floater prototype (A), semi-rigid mechanical connection system with sensor for load measurement (B), mooring configuration and geometry (C), connection system layout (D).

Table 1. Full-scale and 1:50 scaled design parameters.

Parameter	Units	Prototype scale (1:50)	Full-scale
Bathymetry	(m)	0.60	30.0
Floater diameter	(m)	1.08	54.0
Floater height	(m)	0.18	9.0
Floater edge length	(m)	0.54	27.0
Draft	(m)	0.12	6.0
Three platform layout length	(m)	2.92	146
CoG distance from the deck	(m)	0.04	2.12
Distance between platform	(m)	0.06	3.0
Floater pitch inertia	(kgm^2)	8.26	2.58 x 10^9
Floater roll inertia	(kgm^2)	8.26	2.58 x 10^9
Floater yaw inertia	(kgm^2)	13.34	4.16 x 10^9
Floater mass	(kg)	93.20	1.16 x 10^7
Mooring line length	(m)	1.09	54.5
Mooring line stiffness	(N/m)	130	325 x 10^3
Connector stiffness	(N/m)	88500	221 x 10^6

Table 2. Sea states tested during the experimental campaign (prototype scale) and their reference full-scale value.

Sea State	Steepness	Prototype scale (1:50)		Full- scale	
		H_s (m)	T_p (s)	H_s (m)	T_p (s)
IRR01	1:40 Low	0.020	0.71	1.00	5.00
IRR02	1:50 Low	0.022	0.85	1.10	6.00
IRR03	1:50 Low	0.031	1.00	1.50	7.00
IRR04	1:50 Low	0.040	1.13	2.00	8.00
IRR05	1:30 High	0.026	0.71	1.30	5.00

IRR06	1:30 High	0.037	0.85	1.90	6.00
IRR07	1:30 High	0.051	1.00	2.60	7.00
IRR08	1:30 High	0.067	1.13	3.30	8.00

3 Preliminary Experimental Results

In this section the outcomes regarding the comfort indexes in terms of maximum displacement and acceleration are discussed. Regarding the nomenclature adopted in this work to designate the degrees of freedoms (DoFs) of the system, the first subscript stands for the DoF (1 to 6), while the second (n) refers to the platform number of the MMFS: 1 represents the bow platform, 2 the center, and 3 the stern platform.

$$\text{x} = [\text{surge, sway, heave, roll, pitch, yaw}] = [x_{1,n}, x_{2n}, x_{3n}, x_{4,n}, x_{5,n}, x_{6,n}] \quad (1)$$

In order to investigate the comfort parameters of the novel MMFS proposed, the outcomes presented are those regarding the maximum pitch motion and the root mean square (rms) of the measured acceleration for surge and heave DoFs (Fig. 4). Since the experimental tests have been carried out with long crested frontal waves (as sketched in Fig. 1), only the excited degrees of freedom are considered in the analysis: surge, heave, and pitch. In order to assess the system's comfort performance, two references were evaluated for determining comfort criteria: the NORDFOLK criteria for comfort on cruise ships [8], and the criteria presented by the Horizon2020 Space@Sea project study [9].

Table 3. Comfort criteria for floating platforms.

Thresholds reference	Maximum inclination (°)	rms[$\ddot{x}_3$] (m/s^2)	rms[$\ddot{x}_1$] (m/s^2)
Space@Sea [9]	1.00	0.15	0.30
NORDFOLK [8]	2.00	0.20	0.30

The experimental results in terms of comfort indexes are shown in Fig. 4, for the three-modules configuration and Fig. 3 for the isolated module configuration. The results demonstrate excellent comfort performance for the analyzed sea states for the three-modules layout. As expected, the surge and pitch motions of the three platforms are very similar because the overall system behaves similarly to a rigid body due to the stiffness of the connections. In the multi-body configuration, the most critical conditions are represented by the IRR07 and IRR08 sea states for the heave acceleration of stern and bow platforms. On the other hand, referring to the naval cruise boundaries of [8] (second row of Table 3), the only acceleration non eligible becomes the one of the extreme sea state IRR8. Therefore, the system provides excellent comfort and safety performance even for harsh environments and waves up to 2.60 (m) significant height. Instead, for the single floater layout, the comfort thresholds are severely exceeded both with respect to pitch motion and heave acceleration. However, these results highlight how to increase the number of modules for a chosen configuration positively impacts the comfort levels achievable by the system.

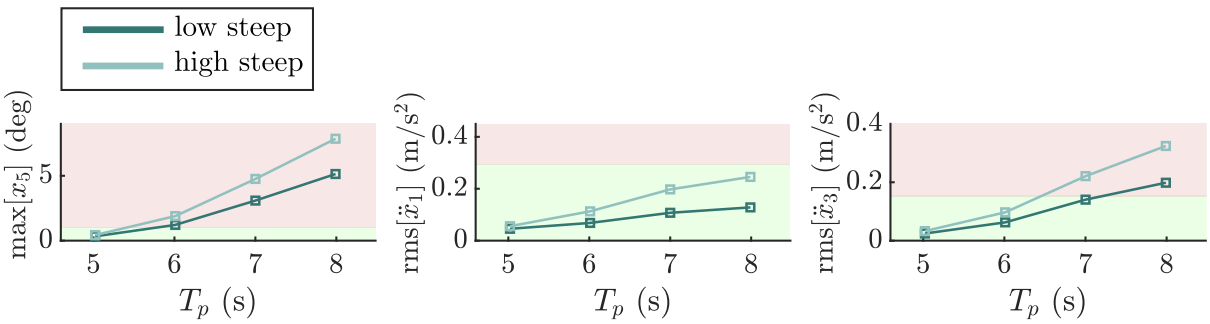


Fig. 3. Comfort indexes for the isolated module layout. The red background color highlights the comfort limit criteria with respect to Space@Sea indications [9].

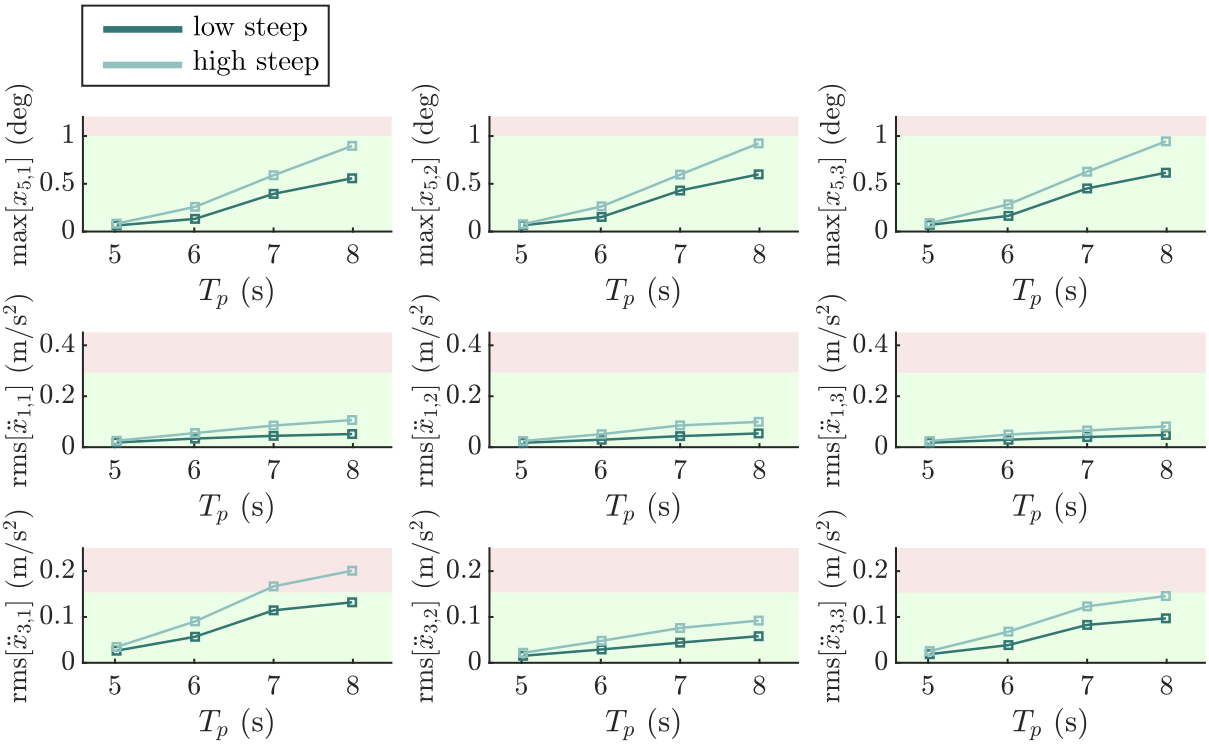


Fig. 4. Comfort indexes for the three-modules in line layout. The red background color highlights the comfort limit criteria with respect to Space@Sea indications [9].

In conclusion, the measured forces acting on the mooring lines and connectors are analyzed for the extreme IRR8 sea state, which is representative of a high stress condition, are shown in Fig. 5. The mooring system, appropriately pretensioned, responds satisfactorily and the condition of slack mooring, which is to be avoided for taut elastic moorings, does not occur. As expected, the highest loads on the connections occur between the first and second platforms (C01 and C02), as these platforms are more significantly stressed by the wave action. Therefore, the system shows a good behavior for the analyzed extreme conditions. Moreover, it is worth emphasizing how these promising results in terms of loads acting on critical systems (such as mooring and connections between different modules) are essential for future system design and optimization.

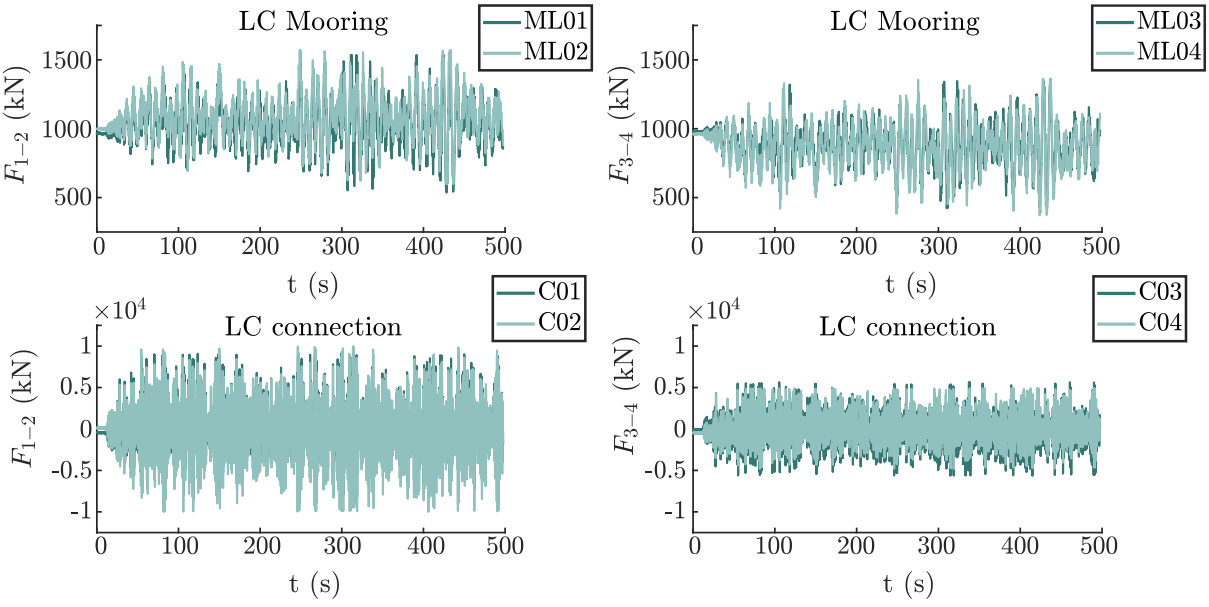


Fig. 5. Measured loads acting on mooring lines and connectors during the extreme IRR8 sea state test.

4 Conclusions and Future Works

This study presents the preliminary results from tests on a 1:50 scale model of an novel MMFS, consisting of interconnected floating platforms with a semi-rigid connector and taut mooring. The experiments investigate two layouts: the isolated module and three modules “in line” configurations. The outcomes reveal that as the number of connected platforms increases, the system provides progressively better performance both in terms of comfort and safety, meeting the thresholds described in [8] and [9] and therefore resulting appropriate for residential purposes. Moreover, this is also true for harsh environments, characterized by waves outside the typical operating conditions, reaching full-scale H_s values equal to 2.60 (m). Then, observing the values of loads acting on critical components of the MMFS such as mooring lines and semi-rigid connections, it is noted that they show promising behavior even when subject to critical working conditions. This achievement is essential for future developments of this research, which will include system optimization. These findings will also inform future studies for calibrating and validating numerical models of the novel MMFS system design.

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