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A novel hardware-in-the-loop device for floating offshore wind turbines and sailing boats

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ABSTRACT

In recent years, the development of CFD simulations has increased the knowledge in fluid–structure interaction problems. This trend has been particularly important for floating offshore wind turbines (FOWTs) and sailing boats. However, especially for these sectors, in which two different fluids are involved, the reliability of CFD prediction tools requires further experimental validations. To this end, as a complementary approach with respect to ocean wave basins, there is the need for wind tunnel aero-elastic dynamic tests.

This paper presents the customization of a 6-degrees-of-freedom (DoF) motion-simulator device for hardware-in-the-loop (HIL) wind tunnel tests on floating scale models. Each step of the machine design-loop is motivated and described: the kinetostatic synthesis is obtained through a multi-objective optimization using a genetic algorithm, the inverse dynamic properties are mapped on the workspace, and finally the drive system is mechanically sized using the so called α–β theory. The emphasis is placed on the mechatronic design methodology, so that different mechanisms and requirements may be considered.

1. Introduction

For the experimental simulation of the dynamic working conditions of hydro-aero-elastic structures, a new testing capability was developed at the Politecnico di Milano wind tunnel (CIRIVE) for its 14 m × 4 m low-speed test section, represented in Fig. 1, where the airflow reproduces civil–environmental conditions. To this end, a 6-DoF robotic device with parallel kinematics, called HexaFloat, was proposed as successor to the older 2-DoF system, presented by Bayati et al. in Ref. [1]. In particular, there is the need to emulate the sea water under scale models of floating offshore wind turbines (FOWTs) and sailing boats, during hardware-in-the-loop (HIL) dynamic tests. To do this, the force and moment components, exchanged between the models and the positioning device, will be measured through a 6-axis balance. Then, with this measure, the hydrodynamic problem is solved in real-time to provide the reference motion for the actuators.

The application context for FOWTs and the sector motivations are presented by Bayati et al. in Ref. [2]. In this field, there is the need to deeply investigate the control issues in connection with different mooring systems, to get significant improvements in the efficiency of the energy production. Only in this way, the bigger costs necessary to install and manage floating deep-water wind farms in the large-offshore can be justified with respect to not-floating and near-to-the-coast plants: shorter payback times are fundamentals. Solving these issues in the next years will transform the promising sector of FOWTs in one important reality of the energy production world.

The design process of a machine starts always from a given set of requirements and iteratively returns to them until the matching between the desired performances and the actual ones is considered satisfactory. When this process is conducted with a mechatronic

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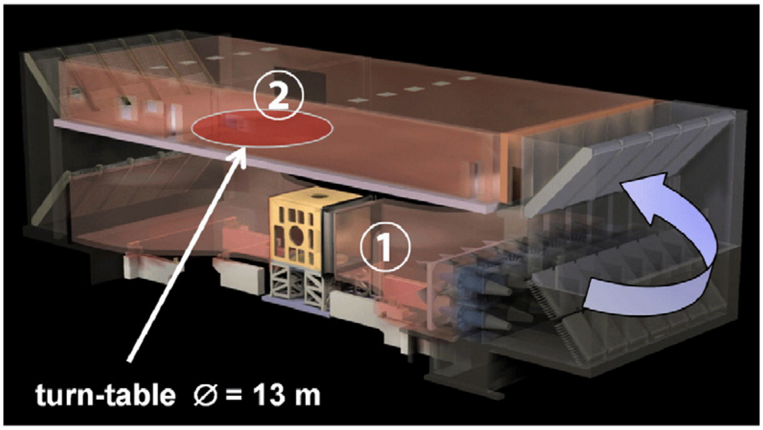

Fig. 1. Politecnico di Milano low-speed wind tunnel (CIRIVE): (1) aeronautical test section, speed = 55 m/s — dimensions = 4 m × 4 m; (2) civil-environmental test section, speed = 14 m/s — dimensions = 14 m × 4 m.

approach it means that mechanics and electronics issues are considered at same time in a multidisciplinary and integrated way, as described by Giberti et al. in Ref. [3] using as a test case the mechatronic design of a 2-DoF-5R PKM.

The preliminary specifications for the HexaFloat are showed in Table 1: the robot is required to position its tool center point (TCP) and to orient its end-effector within the six-dimensional desired workspace (WSd) showed in Fig. 2. Also maximum motion frequencies are given. In addition, it is necessary to stay low with the TCP in the vertical direction because it is not possible to place the robot outside of the wind tunnel test section, which has a limited height of 4 m: the more the workspace is low, the more the usable height of the test section is wide, allowing a convenient geometric scaling of the aerodynamic models. The usable zone extends from the so-called flat-ground, under which all the instrumentation and also the robot will be hidden, to a height close to the ceiling, but far enough away from it, to not encounter the ceiling boundary layer. Finally, it is worth noting that HIL dynamic tests on FOWTs and sailing boats represent a new field of research, without a consolidated literature. This means that the previously described requirements may significantly change, especially after a first experimental phase. Therefore the design process and the machine itself had to be flexible and reconfigurable, to possibly achieve a different desired workspace.

All this requirements led us toward the field of parallel kinematic machines (PKMs), because of their potential advantageous features. PKMs often occupy a complementary position with respect to serial robots, in the sense of higher loading capabilities, achievable velocities and accelerations, positioning accuracy and component modularity. However, these kinds of robots have been always devoted to specific tasks, such as flight and driving motion simulators, micropositioners and pointing systems, without a widespread diffusion, especially in the industrial sector. This is due to a more complicated and less well-established design phase in connection with some critical aspects, which can be summarized as follows: the workspace is little with respect to the overall size of the machine; big end-effector linear displacements are often in contrast with big end-effector rotations (e.g. linear delta vs. parallel wrists); the usable workspace is limited by singular poses and interference problems, especially the link-to-link risk of collision; the anisotropic behavior determines low overall dexterity; the passive joints are key elements in determining the boundary of the workspace because of their limited mobility ranges. All these disadvantageous features make PKMs poorly flexible to task modifications, so that they are rarely available on the market as standard ready-to-use solutions and require a deep customization phase (e.g. PKMs as machine tools [4]). Therefore, there is the need for design methodologies that can overcome long times, uncertain results and high development costs.

This paper presents the steps of the HexaFloat design-loop, whose flow diagram representation is showed in Fig. 3. The 6-PUS architecture is chosen and deeply investigated. Doing this, we traced a possible way to make effective the PKMs' advantages, while overcoming their disadvantages, with the aim to best meet the given requirements. The next sections are organized as follows. Section 2 deals with the Hexaglide kinematic architecture: the motivations of its choice, the solution of the inverse kinematic problem,

Table 1
Desired sinusoidal movements.

Max. zero-peak amplitudes and max. frequencies			
	Wind turbine	Sail-boat	Bridge
f max [Hz]	0.7	1.5	3.0
A_x [m] — //wind	0.50	–	0.01
A_y [m] — ⊥ wind	0.30	–	0.01
A_z [m] — vertical	0.25	–	0.01
A_α [deg] — roll	15°	5°	3°
A_β [deg] — pitch	15°	10°	3°
A_γ [deg] — yaw	15°	10°	3°