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Industry 4.0: advanced digital solutions implemented on a close power loop test bench

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Abstract

The paradigm of Industry 4.0 allows to increase the efficiency and effectiveness of the production. Companies that will implement advanced solutions in production systems will increase their level of competitiveness and will be able reach high market shares. The present paper is focused on the development of advanced digital solutions to be implemented on a close power loop test bench designed to test high power transmissions for naval unit. In particular, the test configuration consists of a back-to-back connection between two identical mechanical reducers. Since the efficiency of these systems are very high, it is not necessary to use large electric motors, thus managing to contain the operating costs of the testing phase. The particular test bench allows to size the electric motor simply based on the dissipated power by the kinematic mechanisms. By means of suitable sensors installed on the test bench it is possible to extrapolate countless technical data. The implementation of Industry 4.0 enabling technologies allows to evaluate the increase in efficiency compared to traditional systems in terms of reduction of noise and vibrations, efficiency of lubrication, reduction of consumption, installation and maintenance cost of the entire system.

Keywords: Industry 4.0; Shipyard 4.0; Internet of things; digital transformation; Test bench; Sustainability; Cad modeling; Experimental tests.

1. Introduction

Since the term Industry 4.0 (I4.0) was introduced in 2011, researchers and scholars from all over the world also look closely at the fourth industrial revolution [1]. The impact of I4.0 today goes beyond the frontiers of the industrial production and it affects all industrial sectors by supporting smart factories [2,3]. The enabling technologies of I4.0 can effectively contribute to the digital transformation of an organization [4-6] with the goal of sustainable

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development [7-9]. The so-called fourth industrial revolution is bringing progress in digital technologies that will radically change the traditional architecture of production [10].

Among these, the Internet of things (IoT), cloud computing, the big data analytics, etc. and, the use of sophisticated sensors, to obtain important information from process data [11] that can be used to improve both the production process [12] and the quality of the final product [13]. The introduction of I4.0 enabling technologies in shipyards is now necessary in order to improve production performance and cost competitiveness [14,15]. In order to realize a smart shipyard, it is surely necessary to constitutes an expert environment for smart ship design [16].

The aim of the work is the preliminary implementation of the I4.0 technologies on a test bench capable of testing and validating an innovative high power azimuth thruster in order to determine a preliminary digital transformation of a shipyard. The thruster system is one of the most critical components of an HSC naval unit. In almost all commercial applications, the propellers of the naval unit are directly driven by a shaft that connect them to the inverter located downstream of the engine. This solution, as verified by CFD analysis [17,18] and towing tank tests with small scale prototypes, determines high fluid dynamic losses. The studied thruster, on the other hand, is constituted by a complex kinematic chain positioned within profiled structures. The complexity of the system required the engineering of an innovative test bench for the detailed design and final testing of all the transmission components.

The thruster was designed and built on a scale of 1:1 and, once tested, it will be installed on a High Speed Craft (HSC) for passenger transport. Through the test bench it was possible to carry out both the experimental tests and the final product testing. In order to satisfy the market, important objectives have been set: to increase the performance of the propulsion plant and make it more efficient, to undertake a path for gradually improving the green footprint and, moreover, to improve the production processes at company level. It is, therefore, a real digital transformation of manufacturing that not only involve the productive side of the shipyard. In fact, since the data collected during the experimental tests can be transmitted directly to the technical office, the engineers are able to analyze the data in order to improve the performance of the entire propulsion system or some critical components. This shows that there are many challenges and opportunities that the industrial world can seize (e.g. resource efficiency, costs, work organization and synchronism between ICT and people) to start a sustainable development with I4.0 [19]. Together with the efforts made to monitor the propulsion system during its operation [20-23], all this certainly contributes to the innovation induced by I4.0 also in the shipyard (Shipyard 4.0).

2. The thruster system and the test bench

In the last years, important technological innovations have allowed to the High-Speed Crafts (HSCs) and in particular at the hydrofoils to become competitive again [24-28]. In order to increase the hydrodynamic performance of the craft, the thruster is realized in a C-drive configuration with the main transmission components housed inside shaped structures. In particular, the thruster is designed to transmit power close to 2000 kW and rotation speed close to 1000 rpm. The kinematic drive has a first reduction realized by a bevel gear positioned in an aluminium alloy box placed inside the hull (upper gearbox in Fig. 1), and a second reduction realized by bevel gears housed in a profiled box at the lower end of the stern strut. The propeller shafts will be installed in the lower gearbox in a contra-rotating configuration.

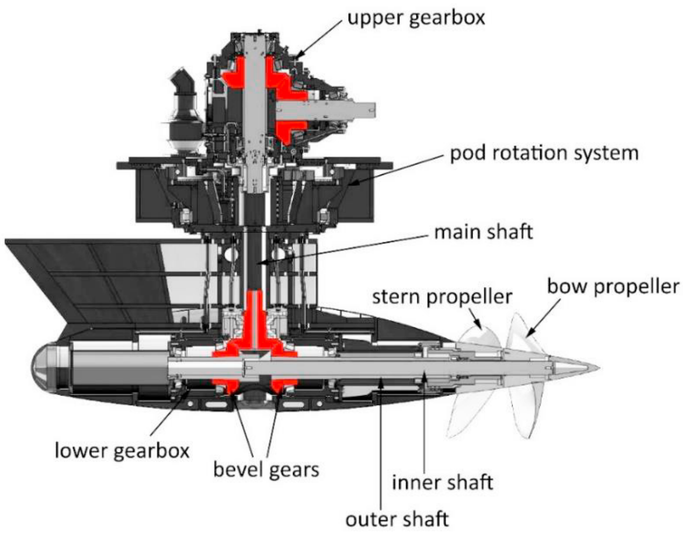

Fig. 1. Kinematic configuration of the studied POD drive train.

The struts connecting the lower gearbox of the thruster to the hull are realized with boxed and welded steel structure, while the lower gearbox containing the transmission components is made of cast EN 43300 T6 aluminum in order to reduce costs and speed up the production process. Composite materials [29-32] with carbon fibers and epoxy resin were used for the drive shaft inside the hull, i.e. for the shaft that connects the output of the engine to the upper gearbox. The inner bearing seats of the lower and upper gearboxes are machined by computerized numerical control machines in order to allow the housing of the shafts of the contra-rotating system.

The optimization of the studied thruster is directly related to the evaluation of important parameters such as efficiency, size and cost. It is therefore essential to use a test bench in order to test the transmission components with the same loads that replicate the real operating conditions.

The technique of transmitting maximum power through a given gearbox by operating the actual application is known as a power dissipation test. When the rotation speeds and rated power of a given transmission are relatively low, the power dissipation test is preferred to other solutions, often more expensive. On the other hand, when the rated power of the gearbox is very high, the power dissipation test often becomes impractical because it is necessary to have a motor unit and a high power braking unit; the test equipment become expensive and a large amount of power has to be dissipated in a hydraulic brake [33] or dynamometer during testing. Among the various possibilities available on the market, close power loop test benches are those that allow you to test transmissions with high rated power while containing operating costs. This kind of mechanical test bench requires the implementation of a back to back connection between two identical gearing (main and secondary, see Fig. 2).

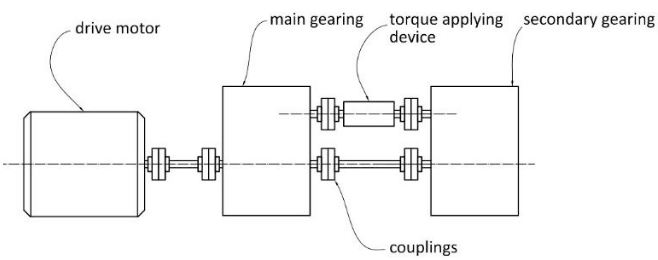

Fig. 2. General layout of the mechanical close power loop test bench.

In this test, the two gearset to be tested are connected to each other in a close loop circuit and the rotation of the connecting shafts starts before that a mechanical system (torque applying device) applies the torque generated during operation. In particular, the torque applying device has been specifically designed for the studied application. The existing devices are very different from each other and mainly differ in totally mechanical and hydraulic systems. The designed torque applying device differs from those available in literature [34] in that the relative rotation of the end flanges, which generates the test torque, is achieved by means of an innovative kinematic system (patent application number 102019000011031). Fig. 3 shows an overview of the assembled test bench and a detail of the torque applying device.

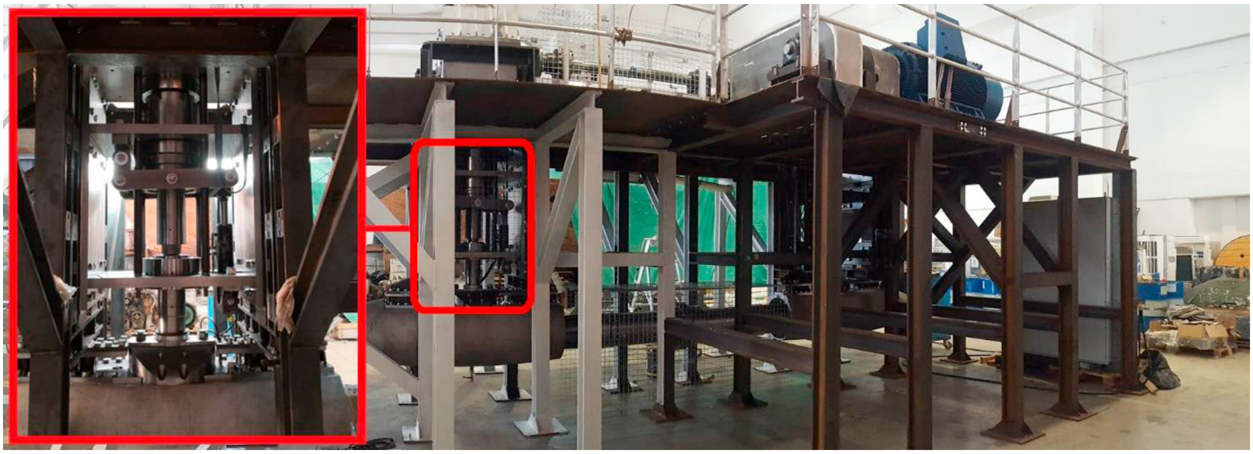

Fig. 3. Overview of the assembled test bench.

3. Preliminary experimental tests and data analysis

During the experimental tests, electrical strain gauges were installed on the test bench frame and on the pod struts in order to compare the experimental strains with those obtained from finite element analysis. Moreover, the torque values were measured using strain gauge rosettes (see Fig. 4) and torque transducers installed on the drive shafts.

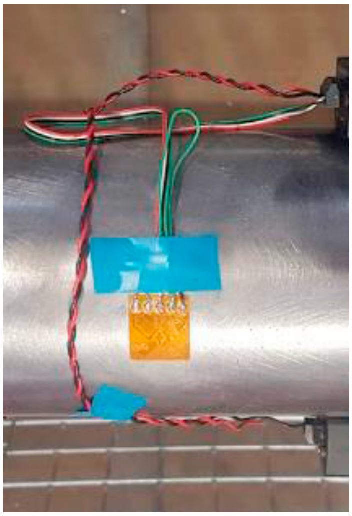

Fig. 4. detail of the electrical strain gauges installed on the shafts of the thruster

Optimum lubrication of the transmission components during power transmission plays a key role in the proper functioning and long service life of the rolling bearings. In fact, one of the tasks of lubrication is to create a film thickness to separate two contact surfaces and thus prevent wear and, consequently, a premature fatigue failure. In addition, proper lubrication helps to remove heat from the internal elements, allow proper heat exchange and ensure that the bearing works at optimum operating temperatures during operating life. A quick identification of a sudden temperature increase could be essential to prevent bearings damages and the consequent technical failure of the thruster.

The cylindrical roller bearings and the single row tapered roller bearings used in the thruster design are thermally stabilized up to temperatures close to 150°C. This value represents, therefore, a given limit beyond which damage to the rolling elements or rapid wear of the raceways could occur and consequently the running quality could be compromised.

The study has allowed to evaluate the geometric configuration, lubrication conditions, etc. which led to a more functional use of the rolling bearings selected for supporting the transmission shafts.

Fig. 5 shows the positions where four PT100 thermo-resistance sensors (T1, T2, T3, T4) have been installed for the instantaneous detection of the temperature during operation. In particular, the sensors were installed in correspondence of the cylindrical roller bearings positioned near the contra-rotating propellers.

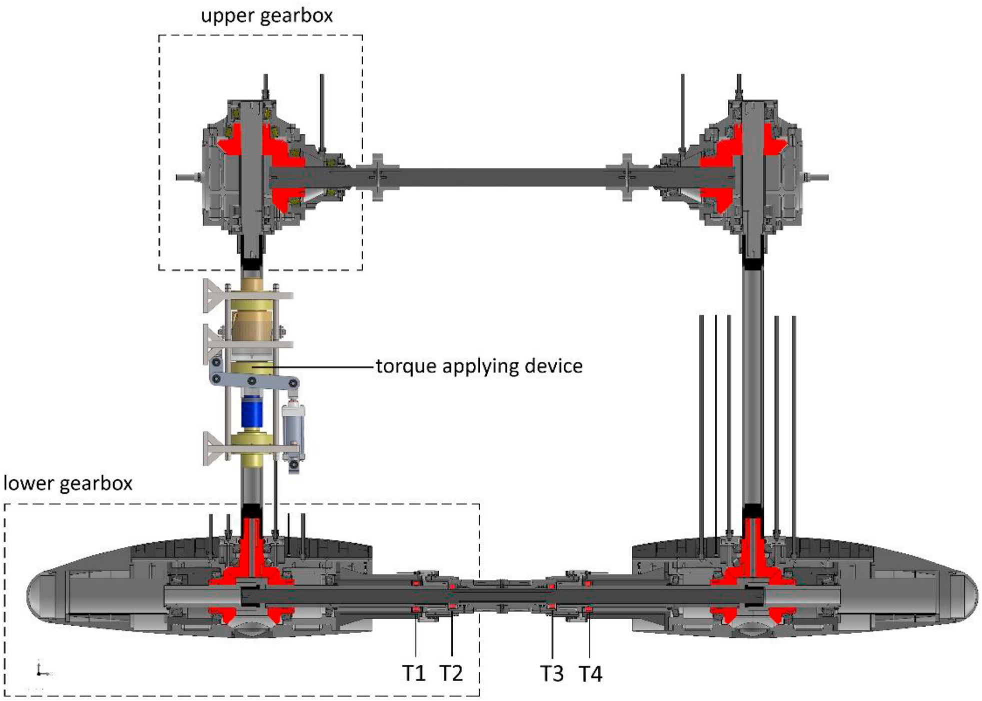

Fig. 5. A scheme of the position of temperature sensors on the thrusters.

The cylindrical roller bearings in which the four sensors were installed, due to their positioning close to the thruster propellers, do not allow the optimal conditions for a good lubricant supply on the contact points between the rolling elements and the raceways.

At maximum motor power and rotation speeds close to 1000 rpm, the possibility of optimal heat dissipation from the bearing is drastically reduced. In order to ensure the operational life of the bearing, more expensive supply and sealing systems are required. These supply ducts should be as short as possible, face directly into the lubrication holes of the rolling bearing and to provide a separate duct for each bearing.

The use of the test bench to test the validity of the adopted solutions has allowed the redesign of the oil inlet ducts and to increase the heat dissipation capacity. In particular, several experimental tests have been carried out by varying the

torque value provided by the torque applying device.
In particular, the electric motor was previously operated with no load, i.e. in the absence of torque introduced into the close-loop circuit. In this phase, the power provided by the electric motor must only overcome the friction in the bearings and gear wheels. The system was kept in rotation for an initial time equal to 10 minutes. The torque was introduced according to the load diagram shown in Fig. 6. The figure shows, in fact, the trend over time of the torque introduced into the system and the power values of the electric motor. The test time was set at approximately 3 hours in which the two thrusters were kept rotating under load.

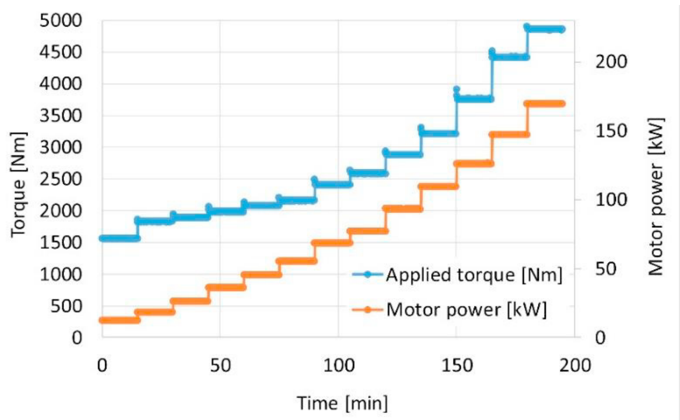

Fig. 6. Trends of the applied torque and of the motor power during the experimental tests.

Fig. 7 shows the temperature values recorded by the four sensors installed in correspondence with the rolling bearings (see Fig. 5).

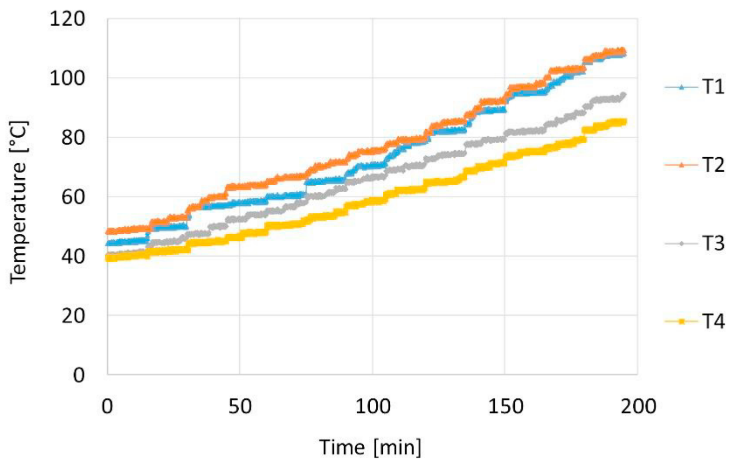

Fig. 7. Temperature values recorded by the four sensors during the experimental tests.

From Fig. 7 it is possible to observe that the T1 and T2 sensors recorded non-optimal temperature values at the end of the test, caused by inadequate lubrication of the bearings. It was therefore necessary to redesign the oil supply ducts in order to ensure more adequate dissipation of the heat produced during the load test. Fig. 8 shows the trend of the new temperature values recorded by the four sensors following the redesign of the oil supply ducts.

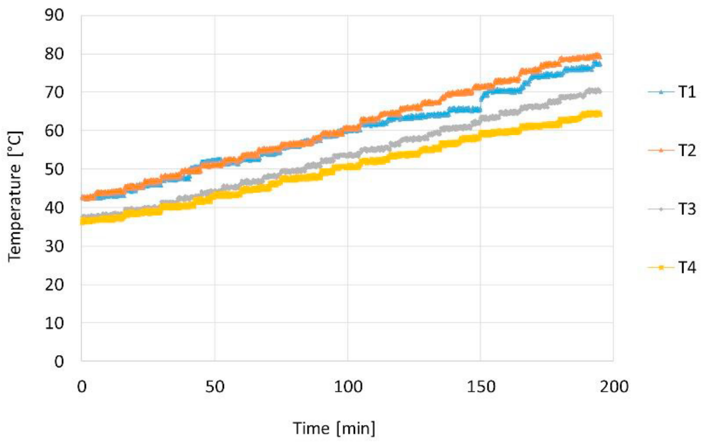

Fig. 8. Temperature values recorded by the four sensors during the experimental tests following the redesign of the oil supply ducts.

With reference to the temperature values recorded by the T2 sensor at the end of the experimental tests, it possible to see that the redesign of the lubrication system allowed a reduction of the temperature values on the bearing of about 27%.

4. Conclusions

A first implementation of I4.0 on a prototype of test bench capable of testing a high power azimuth thruster under full load conditions has been studied, designed and validated. An important investment in IoT sensors was required to collect and to detect a large amount of data. The data analysis has allowed to evaluate the efficiency of the product and the operating process. Once the validation process will be completed, the azimuth thruster will be installed on a high-speed craft for passenger transport. In accordance with the experimental results previously illustrated, the main parameters that was monitored and that affect the efficiency of the system were the strains of the mechanical parts and the temperature. In particular, the analysis and the processing of the temperature data monitored during tests have allowed the redesign of the supply ducts. In more detail, a decrease in temperature values of about 27% was observed. The non-negligible result is related to a longer life of the transmission components with a consequent increase in the effectiveness and efficiency of the entire propulsion system. Other advantages are the decrease in noise levels and vibrations, the reduction of weight, consumptions and maintenance costs.

The preliminary results obtained with the implementation of I4.0 in the propulsion system help the company to achieve the goal of making the propulsion plant more performant, efficient and, consequently, more sustainable. Future studies will concern the realization of a digital twin of the propulsion plant able to overcome the limits of the traditional design which, as is known, requires the realization of many and expensive experimental tests for the validation of the project.

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References

[1] Liao, Yongxin, Fernando Deschamps, Loures Eduardo Rocha Freitas Rocha, and Ramos Luiz Felipe Pierin (2017) "Past, present and future of industry 4.0 - a systematic literature review and research agenda proposal." *International Journal of Production Research* **55** (**12**): 3609-3629.

[2] Yin, Yong, Kathryn E. Stecke, and Dongni Li (2018) "The evolution of production systems from industry 2.0 through industry 4.0." *International Journal of Production Research* **56** (**1-2**): 848-861.

[3] Xu, Li Da, Eric L. Xu, and Ling Li (2018) "Industry 4.0: State of the art and future trends." *International Journal of Production Research* **56** (**8**): 2941-2962.

[4] Basl, Josef (2017) "Pilot study of readiness of czech companies to implement the principles of industry 4.0." *Management and Production Engineering Review* **8** (**2**): 3-8.

[5] Khan, Maqbool, Xiaotong Wu, Xiaolong Xu, and Wanchun Dou (2017) "Big data challenges and opportunities in the hype of industry 4.0." *IEEE International Conference on Communications*.

[6] Duarte, Susana, and Virgilio Cruz-Machado (2017) "Exploring Linkages Between Lean and Green Supply Chain and the Industry 4.0." *International Conference on Management Science and Engineering Management*.

[7] de Sousa Jabbour, Ana Beatriz, Jabbour, Charbel Jose Chiappetta, Foropon, Cyril R.H., and Filho, Moacir Godinho (2018) "When titans meet – can industry 4.0 revolutionise the environmentally-sustainable manufacturing wave? the role of critical success factors." Technological Forecasting and Social Change **132**: 18-25.

[8] Piccarozzi, Michela, Barbara Aquilani, and Corrado Gatti (2018) "Industry 4.0 in Management Studies: A Systematic Literature Review." *Sustainability* **10**: 3821.

[9] Müller, Julian Marius, Daniel Kiel, and Kai-Ingo Voigt (2018) "What Drives the Implementation of Industry 4.0? The Role of Opportunities and Challenges in the Context of Sustainability." *Sustainability* **10**: 247.

[10] Telukdarie, Arnesh, Eyad A. Buhulaiga, Surajit Bag, Shivam Gupta, and Zongwei Luo (2018) "Industry 4.0 implementation for multinationals." *Process Safety and Environmental Protection* **118**: 316-329.

[11] Tao, Fei, Qinglin Qi, Ang Liu, and Andrew Kusiak (2018) "Data-driven smart manufacturing." *Journal of Manufacturing Systems* **48**: 157-169.

[12] Frank, Alejandro Germán, Lucas Santos Dalenogare, and Néstor Fabián Ayala (2019) "Industry 4.0 technologies: Implementation patterns in manufacturing companies." *International Journal of Production Economics* **210**: 15-26.

[13] Hofmann, Erik, and Marco Rüsch (2017) "Industry 4.0 and the current status as well as future prospects on logistics." *Computers in Industry* **89**: 23-34.

[14] Choi, Taihun, and Yoonho Seo (2020) "A Real-Time Physical Progress Measurement Method for Schedule Performance Control Using Vision, an AR Marker and Machine Learning in a Ship Block." *Sensors* **20**: 5386.

[15] Taşdemir, Ahmet, and Serkan Nohut (2020) "An overview of wire arc additive manufacturing (WAAM) in shipbuilding industry." *Ships and Offshore Structures* https://doi.org/10.1080/17445302.2020.1786232.

[16] Perez Fernandez, Rodrigo, and Francisco Josè Regueira (2020) "What the CAD industry can do for the Shipyard 4.0." Sustainable Development and Innovations in Marine Technologies - Proceedings of the 18th International Congress of the Maritme Association of the Mediterranean.

[17] Cucinotta, Filippo, Vincenzo Nigrelli and Felice Sfravara (2018) "Numerical prediction of ventilated planing flat plates for the design of Air Cavity Ships." *International Journal on Interactive Design and Manufacturing*, **12** (**2**): 537-548.

[18] Cirello, Antonino, Filippo Cucinotta, Tommaso Ingrassia, Vincenzo Nigrelli and Felice Sfravara (2018) "Fluid–structure interaction of downwind sails: a new computational method." *Journal of Marine Science and Technology*, **24** (**1**): 86-97.

[19] Stock, Tim, and Guenther Seliger (2016) "Opportunities of sustainable manufacturing in industry 4.0." *Procedia CIRP* **40**: 536-541.

[20] Aiello, Giuseppe, Antonio Giallanza, Salvatore Vacante, Stefano Fasoli, and Giuseppe Mascarella (2020) "Propulsion monitoring system for digitized ship management: Preliminary results from a case study." *Procedia Manufacturing*, **42**: 16-23.

[21] Aiello, Giuseppe, Antonio Giallanza, and Giuseppe Mascarella (2020) "Towards shipping 4.0. A preliminary gap analysis." *Procedia Manufacturing* **42**: 24-29.

[22] Bocchetti, Dario, Antonio Lepore, Biagio Palumbo, and Luigi Vitiello (2015) "A statistical approach to ship fuel consumption monitoring." *Journal of Ship Research* **59** (**3**): 162-171.

[23] Erto, Pasquale, Antonio Lepore, Biagio Palumbo, and Luigi Vitiello (2015) "A procedure for predicting and controlling the ship fuel consumption: Its implementation and test." *Quality and Reliability Engineering International* **31** (**7**): 1177-1184.

[24] Giallanza, Antonio, Giuseppe Marannano, Ferdinando Morace, and Valerio Ruggiero (2020) "Numerical and experimental analysis of a high innovative hydrofoil." *International Journal on Interactive Design and Manufacturing* **14** (**1**): 43-57.

[25] Giallanza, Antonio, Luigi Cannizzaro, Mario Porretto, and Giuseppe Marannano (2017) "Design of the stabilization control system of a high-speed craft." *Lecture Notes in Mechanical Engineering*: 575-584.

[26] Fragapane, Salvatore, Antonio Giallanza, Luigi Cannizzaro, Antonino Pasta, and Giuseppe Marannano (2015) "Experimental and numerical analysis of aluminum-aluminum bolted joints subject to an indentation process."*International Journal of Fatigue* **80**: 332-340.

[27] Giallanza, Antonio, Giuseppe Marannano, and Antonino Pasta (2012) "Structural optimization of innovative rudder for HSC." *NAV International Conference on Ship and Shipping Research*.

[28] Cannizzaro, Luigi, Antonio Giallanza, Giuseppe Marannano, Emanuel Muraca, and Marco Palladino (2012) "Dual compensation control-system for offshore logistic equipment." *NAV International Conference on Ship and Shipping Research*.

[29] Marannano, Giuseppe, and Gabriele Virzì Mariotti (2008) "Structural optimization and experimental analysis of composite material panels for naval use." *Meccanica* 43 (2): 251-262.

[30] Ingrassia, Tommaso, Gianluca Alaimo, Francesco Cappello, Antonio Mancuso, and Vincenzo Nigrelli (2007) "A new design approach to the use of composite materials for heavy transport vehicles." *International Journal of Vehicle Design* **44** (**3-4**): 311-325.

[31] Giallanza, Antonio, Francesco Parrinello, Valerio Ruggiero, and Giuseppe Marannano (2020) "Fatigue crack growth of new FML composites for light ship buildings under predominant mode II loading condition." *International Journal on Interactive Design and Manufacturing* **14** (**1**): 77-87.

[32] Tumino, Davide, Tommaso Ingrassia, Vincenzo Nigrelli, Giuseppe Pitarresi and V. Urso Miano (2014) "Mechanical behavior of a sandwich with corrugated GRP core: Numerical modeling and experimental validation." *Frattura ed Integrita Strutturale*, **30**: 317-326.

[33] Baron Saiz, Claudia, Tommaso Ingrassia, Vincenzo Nigrelli and Vito Ricotta (2015) "Thermal stress analysis of different full and ventilated disc brakes." *Frattura ed Integrita Strutturale*, **9** (**34**): 608-621.

[34] Collins, Laurence J. (1945) "Torque applying device." Patent US2371607.