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

Antonio Giallanza^{a,*}, Giuseppe Aiello^a, Giuseppe Marannano^a

^aUniversity of Palermo, Department of Engineering, Viale delle Scienze, 90128 Palermo, Italy

Abstract

The opportunity 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 develop 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.

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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

* Corresponding author. Tel.: +39 091.23861861.

E-mail address: antonio.giallanza@unipa.it

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 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 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 [14]. Together with the efforts made to monitor the propulsion system during its operation [15-18], 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 at the High-Speed Crafts (HSCs) and in particular at the hydrofoils to become competitive again [19-23]. 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. In the lower gearbox will be installed the propeller shafts in a contra-rotating configuration.

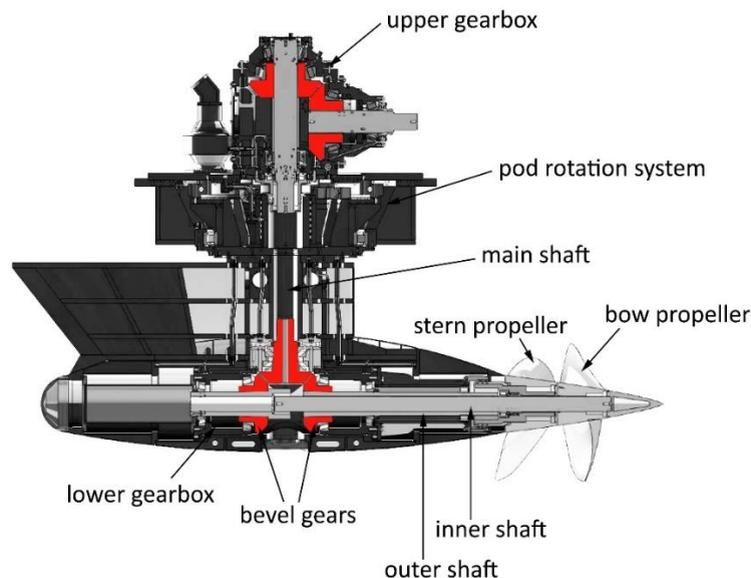


Fig. 1. kinematic configuration of the studied POD drive train.

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 [24–26] 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 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).

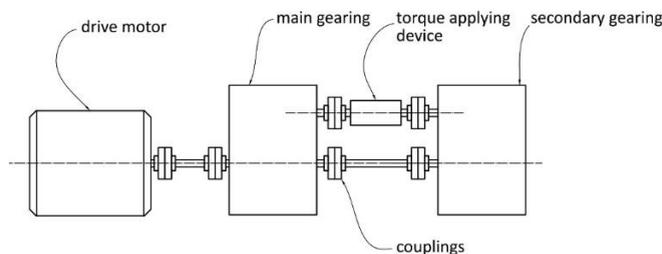


Fig. 2. general layout of the mechanical close power loop test bench.

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 [27] 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.

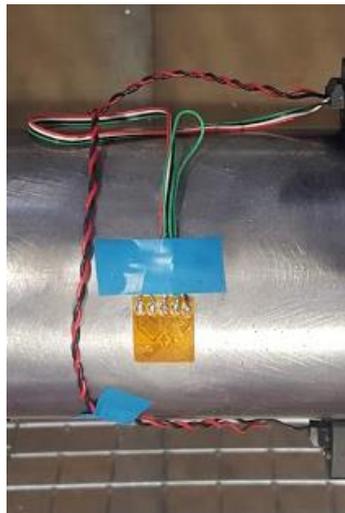


Fig. 4. detail of the electrical strain gauges installed on the shafts of the thruster

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.

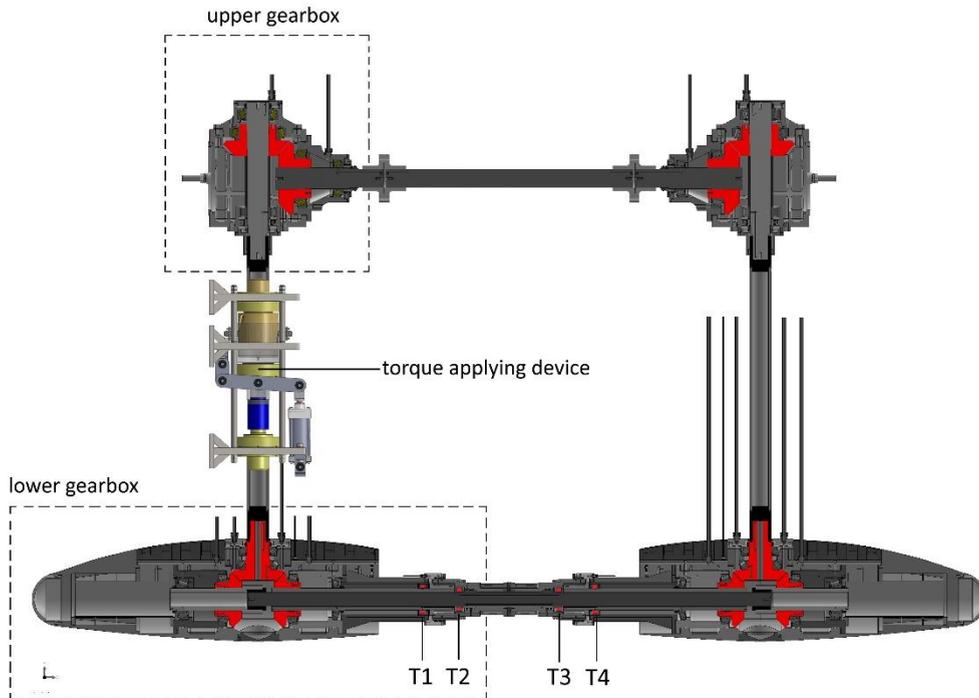


Fig. 5. a scheme of the position of temperature sensors on the thrusters.

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.

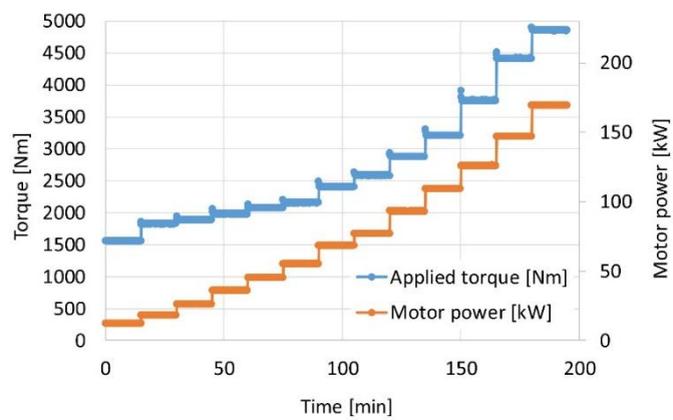


Fig. 6. trends of the applied torque and of the motor power during the experimental tests.

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

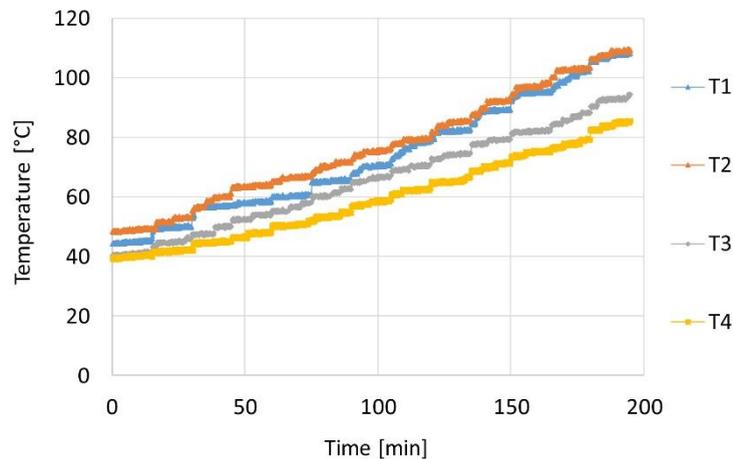


Fig. 7. temperature values recorded by the four sensors during the experimental tests.

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.

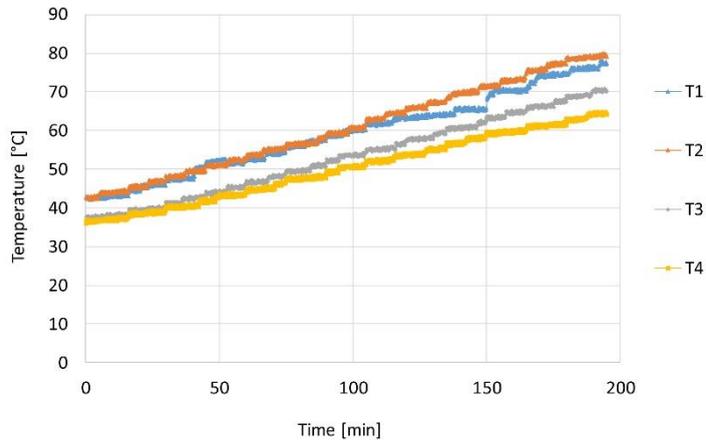


Fig. 8. temperature values recorded by the four sensors during the experimental tests following the redesign of the oil supply ducts.

With reference to the temperature values recorded by the T2 sensor at the end of the experimental tests, it is 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 were 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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