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Design of a Test Rig for Tuning and Optimization of High Dynamics Servo-Mechanisms Employed in Manufacturing Automation

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Abstract

The Industry 4.0 framework is pushing the manufacturing systems towards a zero-defect production based on robot technologies. The increasing level of automation in the production lines is raising new challenges for designers that must face the latest requirements in terms of product quality and power consumption. Among the multitude of components of the industrial plants, Servo-Mechanisms (SMs) play a crucial role and govern important performance indices of both robots and automatic machines. During the execution of high dynamics tasks, the SMs performance is influenced by many factors, including motion law, acting load, temperature and degradation. The development of accurate models aiming at predicting and optimizing the SMs behavior may not be practicable without extensive experimental activities. Owing to these considerations, this work introduces a novel test rig for the accurate characterization of industrial SMs. The rig is designed by combining the advantages of the existing prototypes. It is equipped with high precision sensors and an active loading system that enable to test the SM in various working conditions. Also, the rig modularity facilitates the installation of newly commissioned components and the execution of static and dynamic experiments. The paper mainly focuses on the rig mechanical design and components selection criteria.

Keywords: Servo-Mechanism Test Rig; High Precision Manufacturing; Computer Aided Design; Design methods; Industry 4.0.

1. Introduction

In the Industry 4.0 context, the increasing demand for autonomous, energy-efficient and flexible manufacturing processes is guiding the engineering world into new approaches. The advent of digital technologies and intelligent systems in factories is gradually reforming the modes of production and organization. Furthermore, it is also pushing researchers and designers to develop and adopt innovative design methods and tools aimed at integrating virtual and physical systems to aid smart manufacturing [1,2]. In this scenario, traditional Industrial Robots (IRs) have been progressively converted into a new type of collaborative and reconfigurable devices to deal with the flexibility of modern globalized markets. The need for extremely modular production lines combined with the productivity growth of the last decade motivates the increasing number of IRs, with either serial [3] or parallel [4] kinematic architectures, deployed in manufacturing plants [2]. Following this paradigm, important changes have been made also in the field of automatic machines. In particular, to enable the machines to rapidly modify their task without part substitution, distributed actuation systems are nowadays preferred over previous solutions characterized by fully mechanical drives with complex kinematic chains driven by a limited set of central actuators

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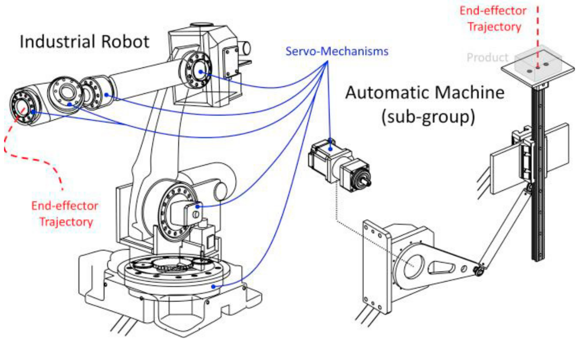


Fig. 1 - Typical industrial applications of SMs.

[5,6]. Therefore, each operational tool is progressively being actuated via a local high dynamics Servo-Mechanism (SM), usually consisting of a servomotor and a reducer [7], as shown in Fig. 1. A clear advantage is that SMs allow to finely tailor the tool motion, effectively adapting the machine to different environmental conditions or product mixes. Differently from standard SMs, high dynamics position-controlled SMs are designed for applications requiring hard accelerations and decelerations.

From a practical standpoint, in addition to the intrinsic difficulties of these macroscopic transformations for both design and implementation phases, the introduction of ever more mechatronic devices (e.g. IRs, SMs and related instrumentations) within the production lines raises the following points that need to be addressed so as to respect the smart manufacturing protocol:

- Develop innovative strategies for the reduction of the overall plant energy consumption (see [5,7–10]).
- Evaluate the performance limitations (e.g. position accuracy errors, thermal drift, etc.) and degradation under different working conditions with the aim to elaborate compensation methods readily applicable to the existing technologies, optimize the design of new ones and predict maintenance interventions [8,11–13].

While several advances have been made in the last years regarding these topics, as proven by the dense available literature, there are still many unsolved issues. For instance, despite their large application in tasks like pick and place, packaging, palletizing, welding and product inspection, IRs have important motion accuracy limitations that inhibit their employment for precise machining operations [3]. In fact, differently from standard operations, where possible lack of accuracy can be partially compensated through precise kinematic calibrations and the use of properly defined teaching points [14], machining operations result more critical due to the high and continuously variable process loads acting on the robot's end-effector [3,15]. In most cases, these would cause nonnegligible deflections and chatter vibrations as a direct effect of the IRs limited mechanical stiffness, inevitably degrading the product quality. As already known and further specified in [16,17], the dominant contribution for the relatively low robot stiffness is the joints compliance (mainly due to the reducers transmission elasticity), being the links elasticity a secondary aspect. Other factors that seriously affect the dynamic performance of IRs may be summarized into controller limited bandwidth and, most important, joint accuracy [3]. Indeed, the high ratio reducers embedded in every IRs joint (see Fig. 1) introduce nonlinearities into the operation of the drive system, such as friction losses, hysteresis and backlash [18–20]. Since IRs usually make reciprocating motion and are controlled with motor-side feedback [21], such nonlinearities lead to frequent deviations from the programmed operation [11]. Servomotors can also induce vibrations that cannot be easily predicted. In general, the dynamic behavior of both servomotors and reducers shows dependency from a wide range of parameters, including the external applied load, operating temperature, geometrical errors of internal components and state of degradation, which becomes quite important due to the growth of service time [22]. The same parameters have a strong impact also on the power consumption of IRs and automatic machines, as proven in [8]. For this reason, and because of the rather limited or inaccurate information provided in the manufacturers catalogues, many researches have recently focused their attention on the development of either proper parameter identification techniques or advanced behavioral models of servomotors and reducers [5,18,23–25]. In order to effectively conduct these steps, a dedicated and reliable experimental apparatus that allows to control a specific set of process variables becomes essential.

Building upon these considerations, this paper presents the design of a novel test rig for the dynamic characterization of industrial SMs. The proposed rig has been conceived as a modular system that can be used to study the influence of various parameters on the SMs performance. The main advantages over the existent solutions are the possibility to test a large variety of industrial products, rapidly reconfigure the rig layout based on the test requirements and, not least, apply highly customizable dynamics loads. As pointed out in [26], if compared to static tests, dynamic measurements can get much more information as they faithfully replicate the working conditions that the tested components can meet in practical applications. The extrapolated data will be used to generate comprehensive performance maps and, therefore, to validate existing models and elaborate new ones.

The remaining of the paper is organized as follows: Section 2 briefly recalls the existent experimental platforms for SMs; Section 3 discusses the design principles and describes the main features of the proposed test rig; Section 4 provides the concluding remarks.

2. Literature review

As the demand for IRs and SMs continues to increase, servomotors and reducers are receiving more attention. In particular, while permanent magnet synchronous motors can be claimed as the standard elements in industrial SMs, three main groups of high precision reducers are usually considered: planetary reducers, cycloid reducers and harmonic drives. Planetary reducers have desirable qualities such as limited cost and easy installation, though they

Table 1 – State-of-the-art of test rigs for SMs.

Test Rig	*Test Type*	*Loading System*	*Input Side - Performance Limits*	*Load Side - Performance Limits*	*Orientation*
[28]	Static	Servomotor	ND	-	Vertical
[29]	Static	Rod + Mass	-	-	Horizontal
[26]	Dynamic	Magnetic Brake	3000rpm	2000Nm (No high dynamics load)	Horizontal
[23]	Dynamic	ND	3000rpm	ND	Horizontal
[30]	Dynamic	Servomotor	ND	ND	Horizontal
[31]	Dynamic	Servomotor	ND	ND	Vertical
[22]	Dynamic	Magnetic Brake	2000rpm	5000Nm (No high dynamics load)	Vertical
[32]	Dynamic	Magnetic Brake	1640rpm	ND (No high dynamics load)	Horizontal
[20]	Dynamic	Torque Motor	ND	500Nm	Horizontal
[33]	Dynamic	Servomotor	ND	ND	Horizontal
[24]	Dynamic	Inertial+Frictional Load	ND	-	Vertical
[34]	Dynamic	Servomotor	ND	200Nm	Horizontal
[35]	Dynamic	Inertial+Frictional Load	ND	-	Horizontal
This paper	Dynamic	Servomotor (modular system)	4000rpm	2000Nm (high dynamics load) – max calibrated value of the torque sensor	Horizontal

typically need multi-stage solutions to reach the high reduction ratios (>70:1) required in heavy-duty IRs. Given that the reducer size is a primary aspect in robotics, cycloid reducers and harmonic drives are generally preferred due to their compact design. Also, they offer advantages in terms of backlash and efficiency. To extend the range of reduction ratios and further increase the torsional rigidity, cycloid reducers are now combined with planetary reducers to form the two stage Rotating Vector (RV) reducers, which are mostly applied in the heavy parts of IRs. For a detailed comparison of the reducers performance, the interested reader may refer to [2,27].

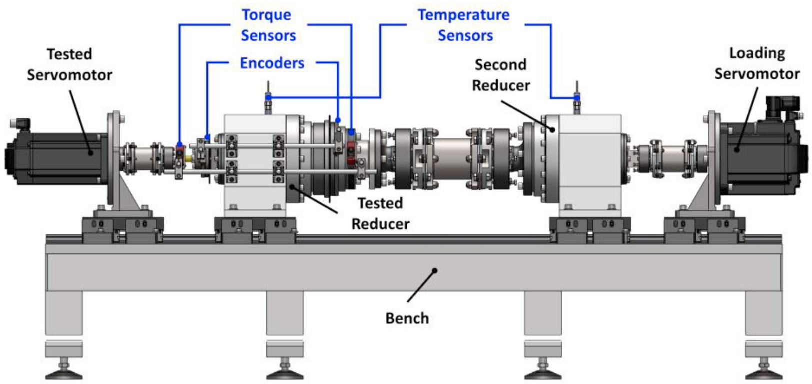
In the last decades, the theoretical knowledge on SMs has been strengthened by focusing on transmission accuracy [29], stiffness [13], stress [36], fault detection [22] and error compensation [25]. Three performance indexes are generally evaluated, i.e. hysteresis curve, rotational transmission error and efficiency. The hysteresis curve is acquired in static conditions and provides important information regarding the reducer backlash, lost motion and torsional elasticity, though a single measurement can only describe the behavior at one angular position. Conversely, the rotational transmission error and efficiency are evaluated during the running state of SMs by installing an appropriate sensory apparatus (encoders and torque sensors) at the input and output sides of the reducer, as described in [26]. As for the considered parameters, some studies have investigated the influence of manufacturing errors (geometrical imperfections) [12], while others have examined the effects of dynamic loads and temperature [8,26]. Generally, the inherent complexity of both servomotors and reducers makes it necessary to confirm the validity of the developed models experimentally. Moreover, being most of the design and operational parameters hidden from the manufacturers, physical testing is becoming even more important in the subsequent steps, namely when the models are to be applied on a real automated system. To meet these requirements, researchers have designed accurate test rigs throughout the years. A summary of their work is listed in Table 1. From a rapid overview, the following considerations can be made:

- The majority of the test rigs can perform dynamic experiments, though only a part of them (see Refs. [20,30,31,33,34]) allows to apply high dynamics (i.e. time-varying) loads. Indeed, in [24,35] the experiments are conducted with the solely inertial and frictional contributions of the transmission, whereas in [22,26,32] additional low dynamics loads are enforced by means of a magnetic brake. At last, the setups shown in [28,29] are valid for measuring the hysteresis curve in static conditions.
- All the test rigs for which the performance is indicated show important limitations. In practice, they can be utilized for testing small-medium sized components. The only exceptions are [22,26], where high torques can be applied but with the aforementioned restrictions (see the previous point).
- To reduce the effect of misalignments on the measured data, some researchers have utilized a vertical layout (see Refs. [22,24,28,31]). However, when dealing with large and heavy components, this may not be the best choice as extra structural supports need to be added, inevitably increasing the complexity of the system. Also, long mechanical transmissions would not be easily accessible for the operators and their components have to be handled with lifting equipment.
- Except for [20], the remaining setups lack flexibility. Essentially, they have been assembled for testing a specific set of components with precise dimensions and torque capacity. Their conversion into different formats requires many design modifications.

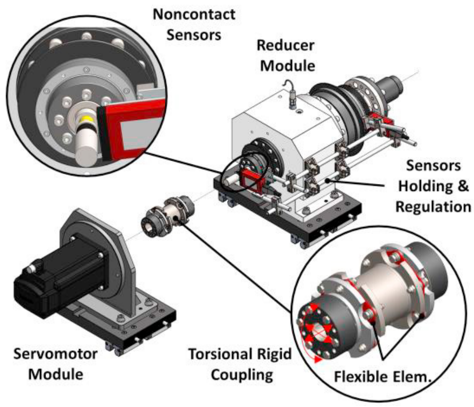
With the aim to overcome the above discussed limitations, in the following a new test rig for SMs is proposed with horizontal layout. Its main characteristics are reported in Table 1 for comparison, whereas its embodiment design will be introduced and described in Section 3.

3. Design of the test rig

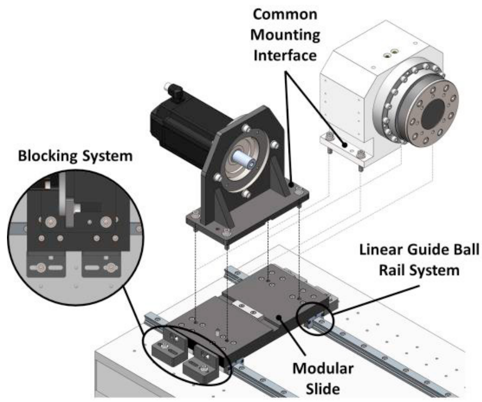
An exhaustive experimental study of the SM performance would necessarily analyze the operation of all its components to understand the influence of each parameter and then establish valid empirical relationships. In other words, a SM cannot be seen as a unique element since each part of the drivetrain (i.e. servomotor, reducer and mechanical coupling) affects the overall system behavior. Therefore, the new measuring system has been conceived to satisfy the following requirements:



(a) Front view.



(b) Main modules and their connection.



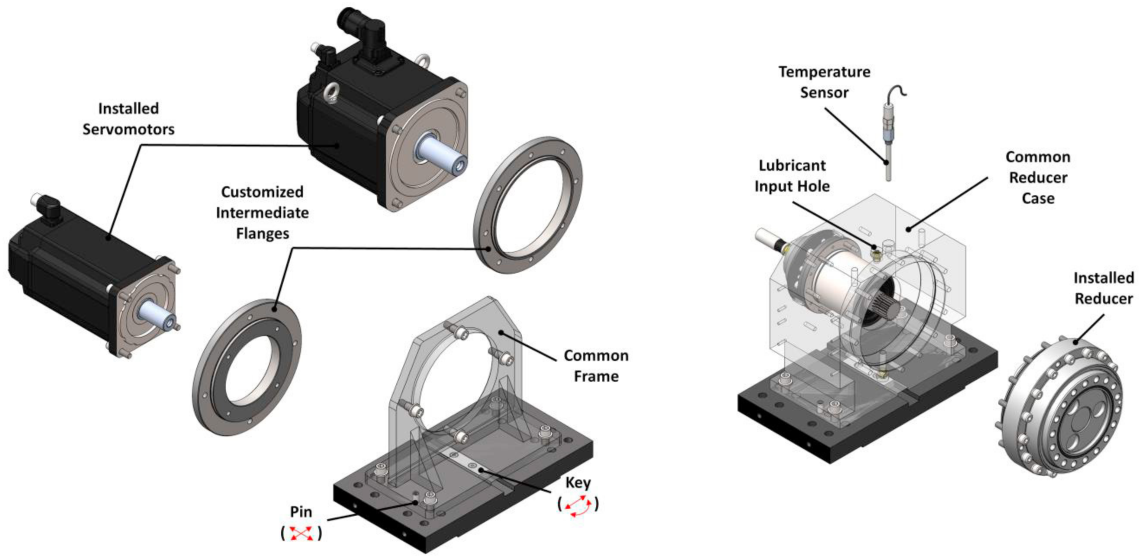
(c) Position regulation system on the bench.

Fig. 2 - CAD overview of the test rig.

1. Flexibility of operation: a multipurpose layout would allow to reconfigure the measuring chain with minimum effort and, if required, to test only a specific subset of parts (even a single component).
2. Wide range of testable devices: to maximize its usability, the rig is to be capable of implementing and testing various commercial SMs, with relatively limited setup time and cost during the assembly phase.
3. Configurable high capacity active load: this mechatronic system is the key element of the rig as it enables to customize each experiment. Its importance arises from the fact that every industrial SM is subject to a specific load, which often varies because of the different product sizes, work cycles and environmental conditions. For example, let one consider the resulting load at each joint when the IR in Fig. 1 works with different imposed end-effector trajectories; the same considerations can be made if the automatic machine shown in the same picture operates with different cycle times, motion laws or product weights. Therefore, in addition to the well-established experimental procedures employing either a static setup or a constant load, dynamic tests which accurately reproduce the realistic industrial time-varying loading conditions become essential steps for a correct understanding of the SMs behavior.

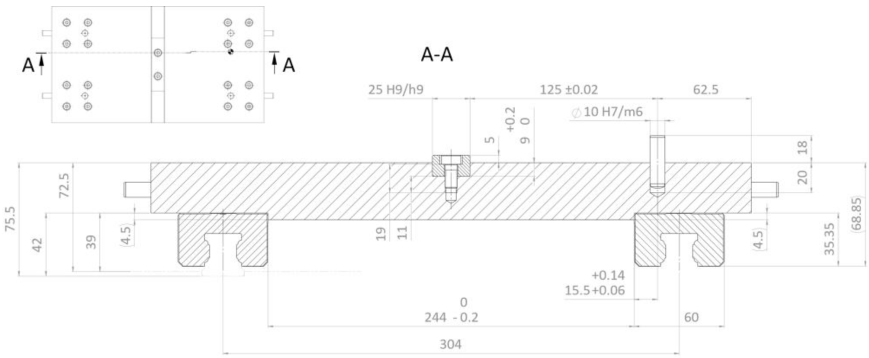
The 3D model of the test rig has been realized in a parametric Computer Aided Design (CAD) software and is shown in *Fig. 2*. All the components are arranged in series and are installed on a horizontal bench (2000×700×740 mm), consisting of a frame made with square steel tubes and a cut steel plate (with flatness<0.1mm). Starting from the left, four main modules can be identified: tested servomotor, tested reducer, second reducer and loading servomotor (Fig. 2a). In practice, the first two modules represent the system under investigation, whereas the remaining ones are used to deliver custom dynamic loads. Each module is connected to the next one with a compact, torsionally rigid, shaft coupling (Fig. 2b) and is mounted on an independent, standard, movable slide, whose axial position is regulated thanks to a high precision linear guide ball rail system (Fig. 2c). These attributes allow to quickly reconfigure the measuring system for different experiments. For instance, one could disengage the active load and then test the transmission(s) with the only inertial and frictional contributions of the target SM. Then, through a short sequence of operations, the full transmission can be restored for further studies. Possible axial, radial and angular misalignments are compensated within the couplers thanks to the flexible disk-like elements installed therewith (see the zoomed view in Fig. 2b), promoting a rapid installation.

As previously discussed, one of the peculiar points of the rig is the possibility to test SMs of different types, sizes and producers. Therefore, modular design principles have been tightly considered to limit the customization to a portion of

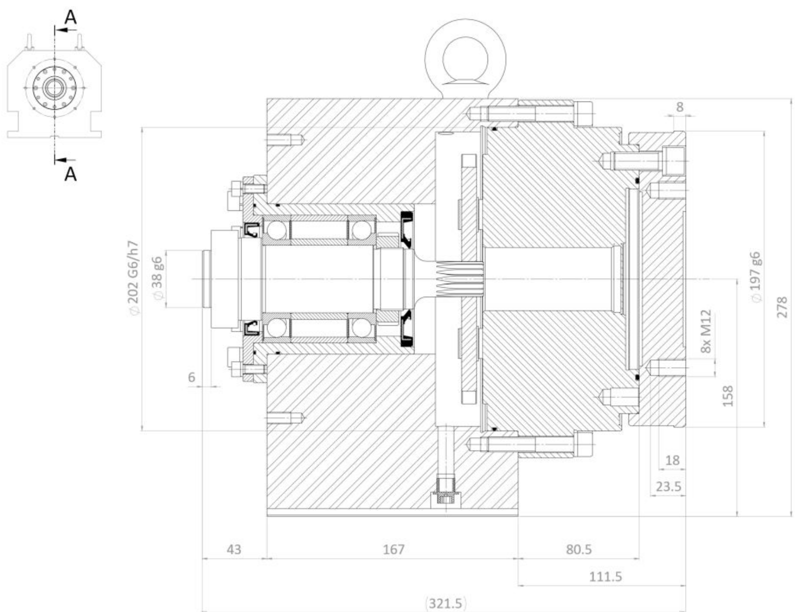


(a) Servomotors mounting system. (b) Reducer case.

Fig. 3 - Modular design solutions.



(a) modular slide: transversal section.



(b) reducer case: longitudinal section.

Fig. 4 - 2D sketch view with principal dimensions.

Table 2 - Equipment installed in the test rig.

Component	*Model*	*Rated/Maximum Velocity*	*Rated/Maximum Torque*	*Additional Info*
Tested Servomotor	Bosch Rexroth MS2N07	2000rpm/4000rpm	22Nm/73.2Nm	Encoder Accuracy: 20arcsec
Loading Servomotor	Bosch Rexroth MS2N10	2000rpm/4000rpm	27.2Nm/70.5Nm	Encoder Accuracy: 20arcsec
Tested Reducer (Red. Ratio 156:1)	Nabtesco RV-160N-156	15rpm/48rpm	1600Nm/4000Nm	Transmission Error: 50arcsec
Second Reducer (Red. Ratio 81:1)	Nabtesco RV-160N-81	15rpm/48rpm	1600Nm/4000Nm	Transmission Error: 50arcsec
Optical Encoder (Servomotor side)	Renishaw RESA 30 ring (Diameter 100mm) Renishaw RESOLUTE angle readhead	ND/9540rpm	ND/ND	Accuracy: 2.86 arcsec
Optical Encoder (Load side)	Renishaw RESA 30 ring (Diameter 200mm) Renishaw RESOLUTE angle readhead	ND/1800rpm	ND/ND	Accuracy: 1.43 arcsec
Torsiometer (Servomotor side)	Manner measuring flange 50Nm Manner AW Dant evaluation unit	ND/8000rpm	50Nm/200Nm	Linearity Deviation: <0.2%
Torsiometer (Load side)	Manner measuring flange 2000Nm Manner AW Dant evaluation unit	ND/8000rpm	2000Nm/8000Nm	Linearity Deviation.: <0.2%
Shaft Coupling (1st-2nd Modules)	Mayr ROBA-DS Size 25	ND/11800rpm	290Nm/435Nm	Torsional Stiff.: 110303Nm/rad
Shaft Coupling (2nd-3rd Modules)	Mayr ROBA-DS Size 300	ND/6200rpm	3500Nm/5250Nm	Torsional Stiff.: 1051909Nm/rad
Shaft Coupling (3rd-4th Modules)	Mayr ROBA-DS Size 40	ND/10100rpm	450Nm/675Nm	Torsional Stiff.: 128731Nm/rad

the system when dealing with new components. The adopted design solutions can be summarized as follows:

- Linear slide: a single type of linear slide with unified mounting interface is used for all the installed modules (Fig. 2c). The correct position of a module onto its locating base is reached by means of a pin and a square parallel key. Then, the module is fixed with four screws (Fig. 3a). The main dimensions of the slide are visible in Fig. 4a. The figure also highlights that the overall positional accuracy of the mating parts (e.g. ball runner block vs. slide and key vs. slide) is referred with respect to the pin, i.e. the reference element for the related machining and assembly operations.
- Servomotor frame: this component experiences high torsional moments, that is why is designed to be rigid and usually results in a very thick and heavy structure. Given that each servomotor has its own mounting flange, to reduce costs, waste of material and space, a universal motor frame is designed. In this way, the intermediate flange (Fig. 3a) will be the only element to be replaced when installing a new servomotor.
- Reducer case: the case housing the reducer (Fig. 3b), custom-designed for specific reducers models (Nabtesco RV-160N), is chosen for its widespread application. Referencing Fig. 4b, the only issues when installing new reducers of the same series may be the differences in the size of the input gear shaft, or in the amount of required lubricant (internal blank areas). The case is designed to provide high coaxiality with the input shaft and consists of a machined metal block that accommodates the input gear shaft and the reducer on the servomotor side and load side respectively. Both these parts are screwed on the case structure and can be easily removed when installing a new product. From the section view of Fig. 4b, two more details can be observed. i) On the input gear shaft, a back-to-back duplex precision bearing arrangement (also known as “O” arrangement) is implemented which ensures equal stiffness in both directions and provides radial and axial rigidity; the correct preload on the inner races is realized via a lock nut retained with a lock washer. ii) An outer hole with a threaded end-cap is placed at the bottom side of the case to facilitate the lubricant removal operation.

The shown rig configuration comprises two Bosch servomotors (MS2N07 and MS2N10) and two Nabtesco RV reducers (RV-160N size with reduction ratio of 156 and 81). Their operative parameters are listed in Table 2. Regarding the loading SM design, in addition to the velocity/torque limits specified in the manufacturers catalogues, also the thermal behavior of both servomotor and reducer must be carefully evaluated to fully exploit the servomotor peak torque. Then, much design effort is commonly placed on the loading SM tuning operations, which necessarily require a multidisciplinary approach that takes into account several interacting factors, namely mechanical system and electric motor dynamics, control law, drive performance, power converter behavior and requested torque controlled motion law [5]. During the experiments, the performance of each servomotor (angular position and its derivatives, provided torque, absorbed power, winding temperature, etc.) can be constantly monitored through the drive system. Nevertheless, the provided kinematic quantities are representative within the servomotor flange and cannot be taken as the reducer input due to the accumulated errors along the measurement chain caused by the slight elastic torsional deformation of each component. Important considerations should be made also for the torque: its value is not directly measured inside the servomotor but only estimated using the absorbed current and the torque constant (which shows a nonnegligible dependency from the operating temperature [5]). Hence, to accurately characterize the reducer performance, a set of noncontact sensors consisting of two optical encoders and two torsiometers (see Fig. 2b and Table 2 for details) has been installed at its input and output sides. At last, to experimentally assess the influence of the lubricant temperature on the SM behavior, a temperature sensor (thermoresistance PT1000) has been inserted inside the lubricant filler pipe of each reducer case [8]. Additional sensors (e.g. accelerometers) can be placed on the surface of the RV to collect vibration data and then perform fault diagnosis [22,33]. Following the industry standards, the signal acquisition and the working states of the servomotors can be handled with a modern programmable logic controller, which permits to synchronize large amounts of data and to rapidly reconfigure the system.

4. Conclusions

This paper presents a novel test rig that is designed to facilitate the performance prediction, analysis and optimization of high dynamics SMs before their use in IRs and automatic machines. SMs represent the core elements of modern manufacturing plants and their performance evaluation is a crucial step to improve the overall system efficiency and product quality. The scope of this research is to define a comprehensive and modular experimental apparatus that can potentially be used for a large variety of servomotors and reducers. After an initial literature review concerning the existent research prototypes, the conceptual design of the new test rig is discussed. Thanks to its modular design and to the use of an active loading system, the rig can be rapidly reconfigured to examine the SM behavior (backlash, compliance, hysteresis, transmission error and efficiency, etc.) under various working conditions. The future work will deal with the physical prototyping of the rig and with the definition of the testing procedures.

CRediT author statement

Mattia Belloni: Conceptualization, Methodology, Visualization. Pietro Bilancia: Investigation, Validation, Writing - Original Draft, Writing - Review & Editing. Roberto Raffaeli: Conceptualization, Supervision. Margherita Peruzzini: Writing - Review & Editing, Funding acquisition. Marcello Pellicciari: Conceptualization, Supervision, Project administration, Funding acquisition.

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