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Researches on the hybrid electro-hydraulic actuators

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Abstract. The new generation of „more electric” actuators involve simpler, cheaper and lighter power generation and distribution architectures. To achieve this goal, the electro hydraulic servovalves controlled by electrical signals have to be eliminated in the frame of the new concept „Power-by-Wire”, which uses electric power to actuate flight control surfaces, robotic arms, steering systems, presses etc. These developments have generated two new types of actuators: electro-hydrostatic (hybrid) actuators (EHA) and electro-mechanical actuators (EMA). This paper presents both the modeling and simulation of an original hybrid actuator, and the static and dynamic performances of a real one with similar electric, mechanic and hydraulic parameters. The simulations were performed for the control of an asymmetrical hydraulic cylinder. The validation experiments were performed on the original test bench. The new concept of the hybrid servosystems was validated by the good accuracy for different type of inputs. The time constant for a step type input signal is good enough for any industrial application.

Keywords: modeling, simulation, design, experimental validation.

1. Modern trends in the structure of the high-performance actuators

The global expansion of manufacturing of digital actuators for aircrafts, motor vehicles, mobile and agricultural machinery, home appliances etc. requires the fabrication of a large number of components with very different mechanical, electrical, thermal, chemical and electromagnetic properties, assembled on flexible automated lines [1], [2], [3], [4]. These modern technological processes include all types of actuators, developing a wide range of forces specific to deformed, injected

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or compacted materials, which need a large amount of energy, with an important share in the value of the products.

The demands of relatively large forces, necessary to realize cycles designed with modern languages, imposed the hydraulic actuation of the active parts with digital servomechanisms whose performances depend essentially on the requirements of the processes [5], [6], [7]. The reliability of modern hydraulic servomechanisms depends on the lubricating qualities and the degree of purity of the working fluids, which can affect the operation of most types of electrohydraulic servovalves.

A major progress in the precision and maintenance of electrohydraulic actuators was achieved after 1990 by replacing the traditional two-stage or three-stage servovalves that include relatively small holes (0.2...0.5 mm) in the control stages with proportional servovalves, whose spools or valves are controlled directly, in position or force, by proportional electromagnets or linear electromotors provided with transducers of appropriate resolution (0.1...1μ).

After the year 2000, digital communication was achieved between high reliability (redundant) controllers, digital position and pressure transducers and proportional servo valves provided with appropriate interfaces. Thus, electrohydraulic presses have been integrated into digital automated production lines, taking materials and semi-finished products from external companies to supply assembly lines for cars, aircraft, household appliances, etc.

The structural and dimensional unification of large series products also allowed the conception of hybrid presses with eccentric, in the sense of its actuation by brushless electric motors (coupled with multi-stage planetary gear speed reducers) and the electrohydraulic cushion actuation. In this way, the major energy consumption of the pumps related to the ram and the consumption of cooling water for the recirculated oil in its hydraulic system, which cannot be missing from the architecture of the high precision presses, can be eliminated.

Efforts to significantly reduce the power consumption of low, and medium-power electrohydraulic servos have led to the patenting and realization of hybrid electrohydraulic servos, which use a bidirectional hydraulic transmission consisting of a constant-capacity positive displacement pump and a hydraulic cylinder. The pump is driven by a brushless servomotor whose speed is regulated according to the position error of the hydraulic cylinder piston (Fig. 1). Thus, the efficiency of the hydraulic servomechanism increases considerably because this structure eliminates the major energy loss through the servovalve (typical - 33%), and the dynamic performance of the system depends on the power of the brushless servomotor and its time constant only (around 0.01 s).

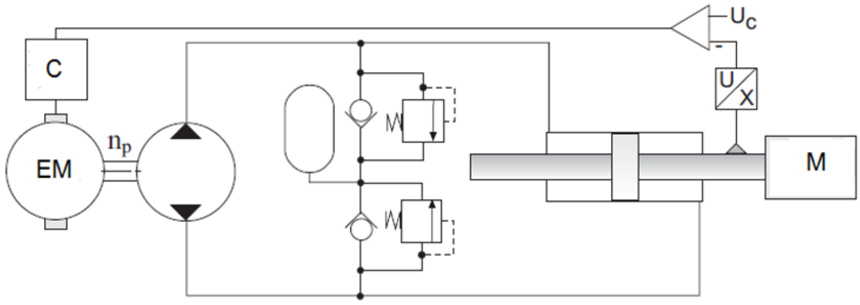


Fig.1. Electrohydraulic actuator (EHA) with electric motor control (EM).

The modern hybrid drive systems used in different type of machines recover the brake energy from the pads using hydrostatic transmissions made from constant capacity bi-directional pumps and reversible brushless electric machines. [8]

The recent progress in the general-purpose family of hybrid servomechanisms extended the actuation power and the actuated load dynamics in the field of the advanced aerospace applications, both civil and military ones (Fig. 2).

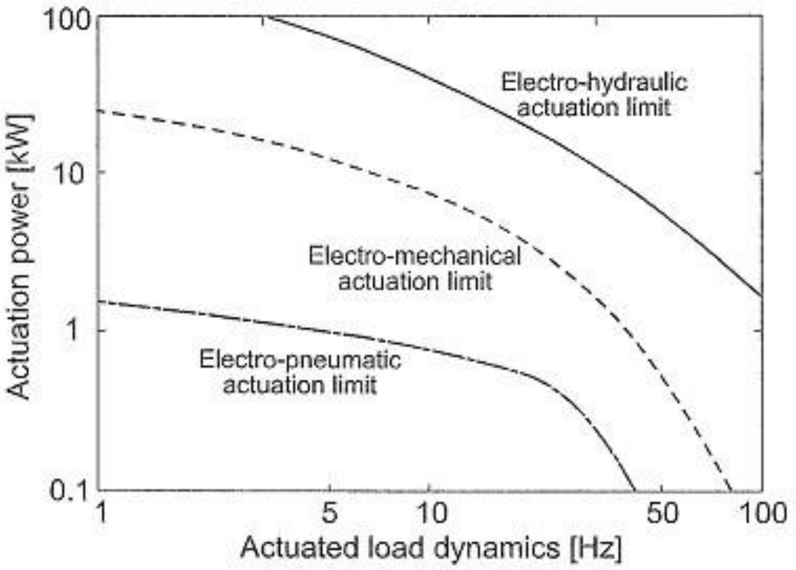


Fig. 2. Typical performance characteristics for different type of servoactuators.

2. Common electro hydraulic schemes of EHA

Symmetrical drive systems (fig. 3, a, b) can be made with ordinary pumps and are driven by classic error compensators or with additional speed reaction.

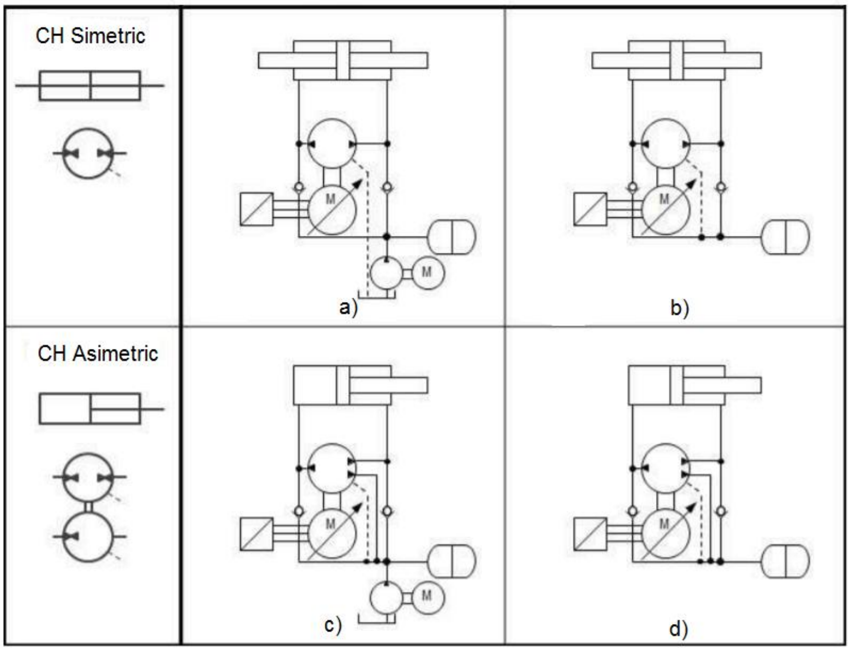
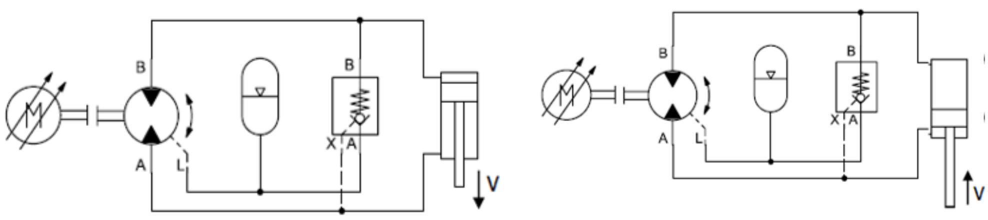


Fig. 3. Schemes of hybrid servomechanisms: with symmetric cylinder (a, b) and asymmetric (c, d)

However, many applications of the hybrid solution use asymmetric hydraulic cylinders, which require large capacity accumulators or directional valves that can be unlocked during the rod retraction phase. Axial piston pumps with inclined disc and valve plates can also be used (Fig. 3, c,d). The simplest solution for controlling asymmetric cylinders is to use a single unlockable directional valve (3-way), which allows the liquid in the accumulator to connect to the large area chamber of the cylinder (fig. 4.a). Retraction of the rod causes the opening of the directional valve and the evacuation of the excess flow from the large chamber into the accumulator (Fig. 4.b). A common compact design of a three-ways valve is shown in Fig. 5.



a) b)

Fig. 4. Asymmetric hybrid system with unlockable direction valve:
a) rod extension; b) rod withdrawal.

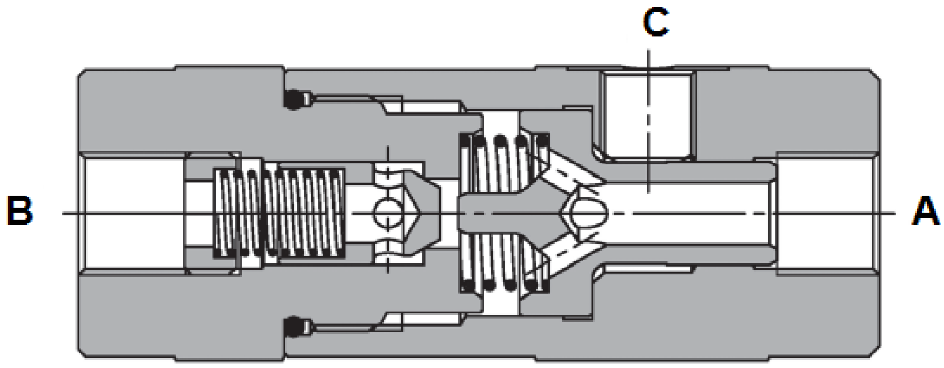


Fig. 5. Main cut view of a single unlockable directional valve.

A more complex scheme of a hybrid servomechanism, shown in Fig. 6 include two four-way unlockable directional valves (SD4) and a three-way flow selector (DD3/3).

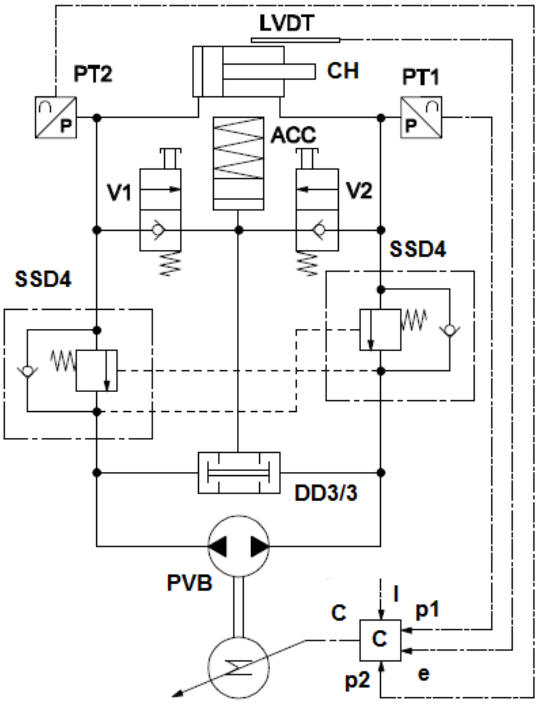


Fig. 6. Experimental hybrid servomechanism with asymmetric hydraulic cylinder [5]

Recent researches performed by Purdue University and Bosch Rexroth Company [6], [7], [8] have shown a way of running in four quadrants with recovery the energy used for covering a variable load (Fig. 7).

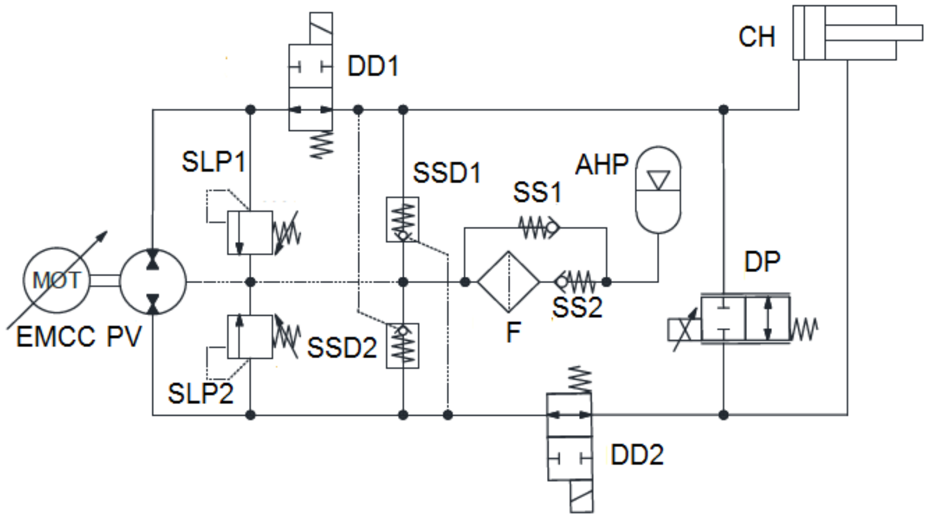


Fig. 7. Experimental scheme of a four-quadrant hybrid servomechanism

A bidirectional, reversible, constant displacement (PV) pump, driven by a bidirectional variable speed electric motor (EMCC) is connected in closed circuit with a single rod hydraulic cylinder (CH). The flow required to compensate for the difference between the area of the piston and the area of the rod section is supplied by a low-pressure accumulator (AHP), fed or drained through two unlockable directional valves (SSD1 and SSD2). Two 2/2 directional distributors (DD1 and DD2) allow the piston to be locked under the action of a random force. The movement of the cylinder is controlled by the four-quadrant servo pump. Pressure Relief Valves (SLP) are provided on both pump connections, on both rod extension and retraction. A miniature proportional distributor (DP), placed in parallel with the cylinder, avoids the pump going out of the normal speed range. The external drain of the pump is connected to the accumulator to conserve the total amount of fluid in the system in any operating mode.

3. Applications of the hybrid servomechanisms

The great progress in the promotion of the EHA become public in 2006 by the launch of the F35 fighter [LM]. The outstanding static and dynamic performance as well as the reliability of the hybrid servomechanism has been systematically confirmed by the use of digital redundant hydraulic equipment specific to all flight control surfaces, eliminating the centralized production of pressurized fluid. Such equipment (Fig. 8) produced by PARKER [9, 10] and MOOG [11, 12, 13], is supervised by a redundant controller included in the digital computer network of the plane. The elimination of hydraulic connections from the extremely small spaces of the aircrafts and the individual maintenance of each equipment essentially simplifies the architecture of their hydraulic installations.

Fig. 8. Redundant EHA for the tail of F35 [11]

The exponential increase in the capacity of civil transport aircraft, completed by the official qualification of the A380 aircraft in 2005, required the development of hybrid electrohydraulic servomechanisms at the highest level of field-specific security (fig. 9.). However, for security reasons, the hybrid servomechanisms related to the horizontal stabiliser were doubled by classic servomechanisms (Fig. 10).

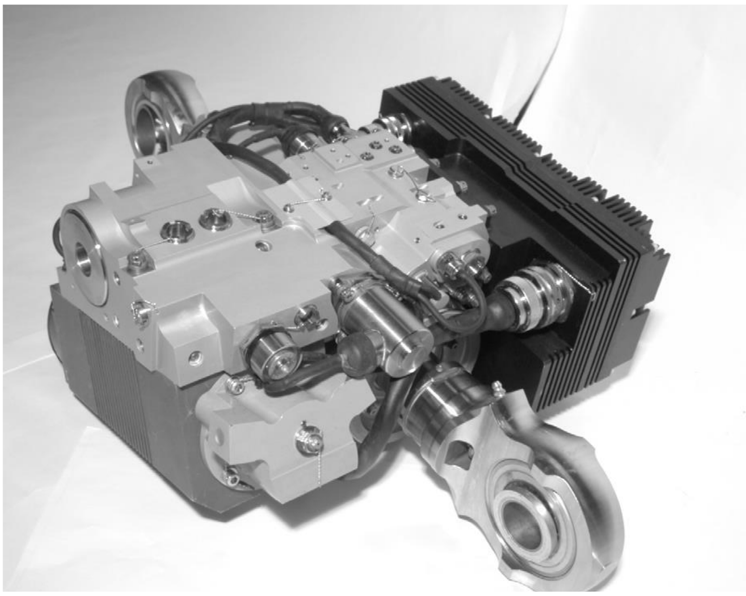


Fig. 9. EHA used in the fly control system of A380 [12]

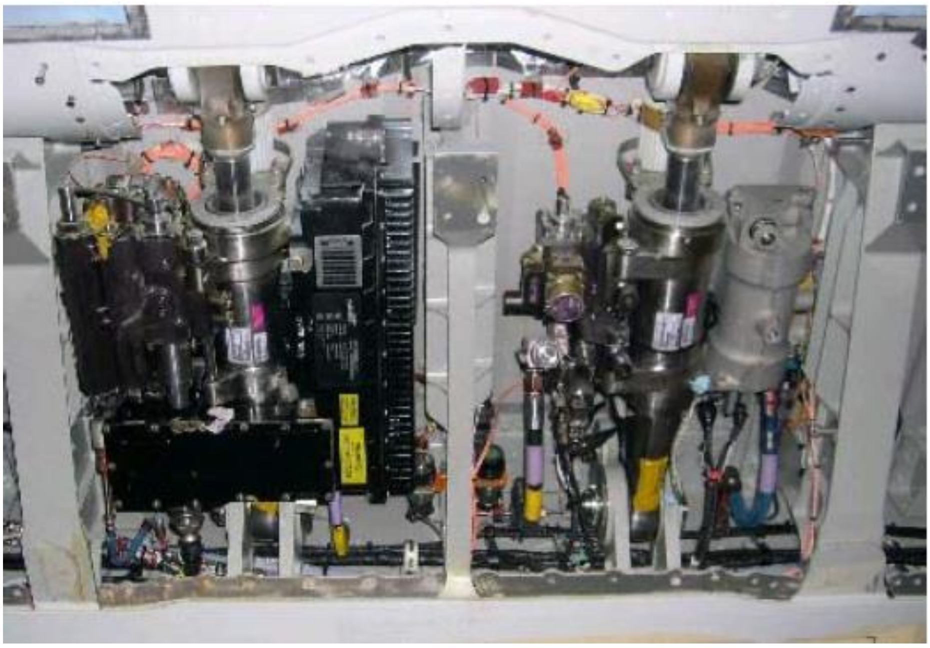


Fig. 10. A pair of EHA and EHSA used on the horizontal stabilizer of A380 [12]

The successful of the aerospace implementation of the EHA generated a new branch of activity in the companies oriented to the fluid power systems. The wide field of applications in presses, robots, mobile equipment of any destination, CNC machine-tools etc. need mature hybrid actuators assembled from high quality series components. Some examples of general-purpose EHA (Figs. 11, 12 and 13) already generated a wide field of industrial applications [14]. One of the most important extensions of the EHA concept is the hybrid steering system introduced in 2016 by VOLVO [15] for autonomous driving of the trucks (Fig. 14). A brushless motor is included in the steering columns of the truck or bus for controlling a classical hydromechanical servomechanism with rotary servovalve (Fig. 15). The controller of these systems has at least two inputs: the steering wheel angle and a GPS dedicated system. Other sensors as LIDAR type are integrated in the driving controller.

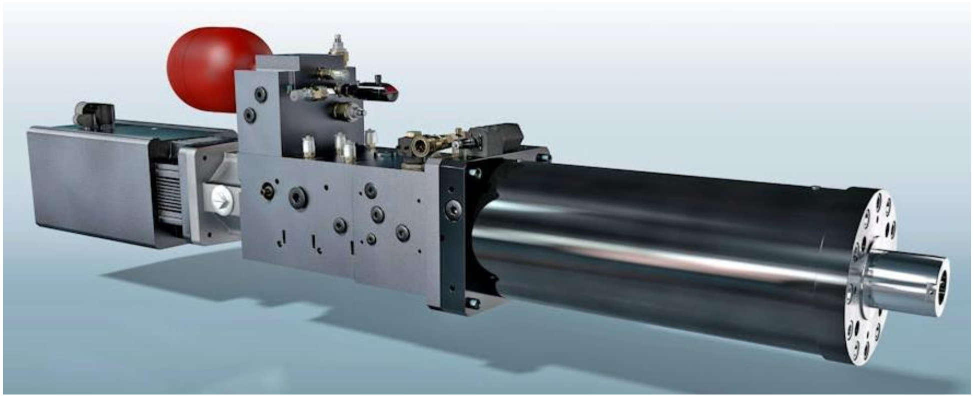


Fig. 11. General purpose EHA with axial pistons pump and asymmetric hydraulic cylinder [13]

Fig. 12. Universal small power EHA with asymmetric cylinder [14]

Fig. 13. EHA with asymmetric cylinder for high accuracy presses [14]

Fig. 14. Complex hybrid steering system for autonomous driving [15]

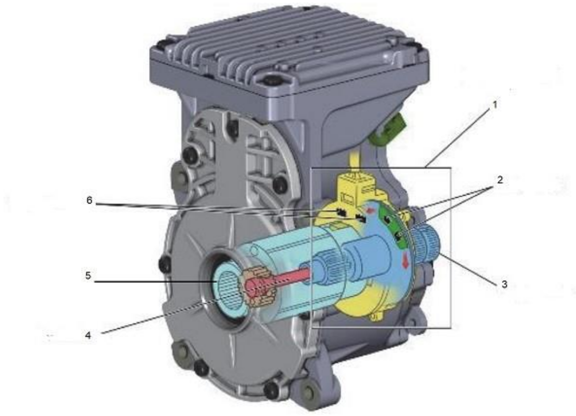


Fig. 15. Brushless servomotor designed for autonomous driving trucks:
1 – torque and angle sensor; 2 – Hall sensors; 3 – steering wheel shaft coupling;
4 – torsion bar; 5 – output shaft; 6 – Hall sensors. [15].

4. Modeling, simulation and testing of an asymmetric EHA

Numerical simulation with a control language as Simulink, FluidSIM or Simcenter Amesim [16, 17] is always a preliminary stage for the design, manufacturing and testing the experimental model of any electrohydraulic actuator. The authors designed and tested an experimental axisymmetric EHA. The simulation network designed in Simcenter Amesim for the asymmetric configuration is shown in Fig. 16. The main features of the network components are as follows: the type of electric motor: DC, brushless, with permanent magnets, bidirectional, with natural cooling and with built-in tachogenerator; type of electric motor controller: digital, with automatic limitation of motor speed and current, with analog and digital feedback inputs; position loop controller type: analog or digital; volumetric pump type: with bidirectional involute gears, with floating bearings to compensate for frontal wear and minimize the volume of liquid squeezed in the gearing area, with internal drainage system and double external sealing of the shaft for the maximum pressure from the internal drain; type of accumulator: with rubber membrane, pre-charged with nitrogen; type of pressure limiting valves: single-stage, with compensated conical poppet; three-way directional valve type: route, with uncompensated conical valve and hydraulic release at a low-pressure command; hydraulic cylinder type: differential, with elastomeric seals and PTFE guide bushings for the piston and the rod; piston rod position transducer type: resistive, with two tracks, with infinite resolution; type of elastic load: helical spring located "in a box". The objectives of the numerical simulations are the following: assessment the quality of the static characteristic, the accuracy of the response to sinusoidal signals of variable amplitude, and the response time for step input signals of variable amplitude.

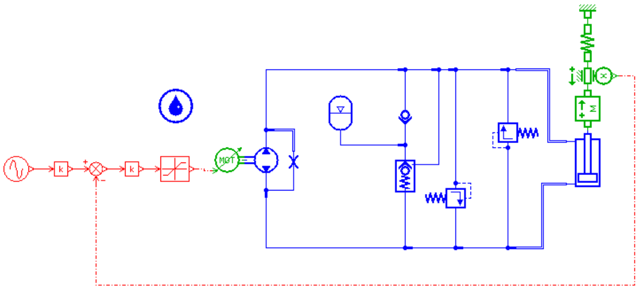


Fig. 16. Amesim simulation network for the experimental test bench of the EHA.

The static characteristic obtained with a low frequency sine signal indicates a good enough accuracy for industrial applications (Fig. 17). The simulated response to different amplitude sine signals (Fig. 18) show a good following accuracy. The response of the EHA for different step inputs shows also a good dynamics (Fig. 19).

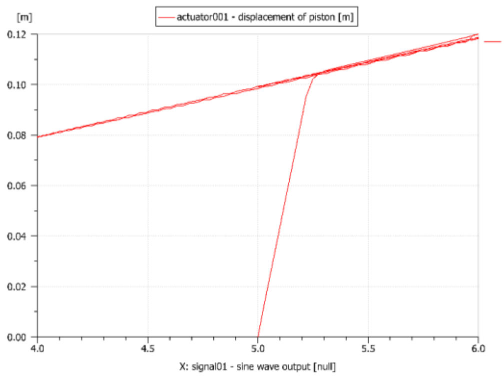


Fig. 17. Static accuracy of the actuator obtained with a low speed linear input.

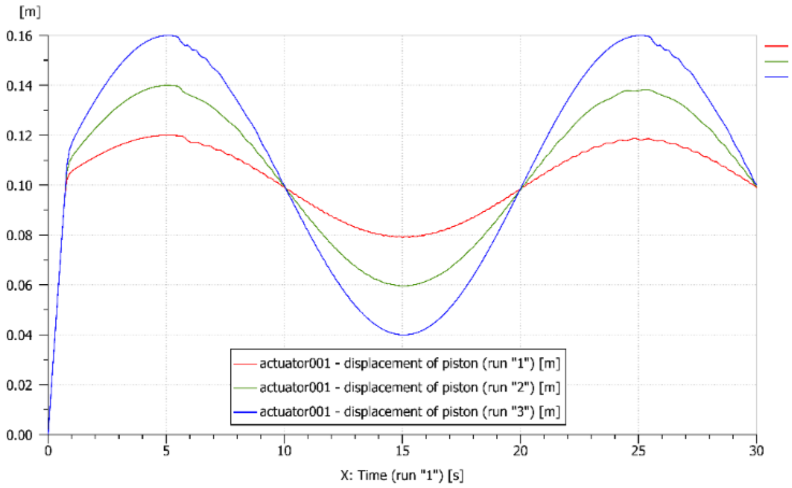


Fig. 18. Simulated responses of the EHA for different amplitudes of sine inputs.

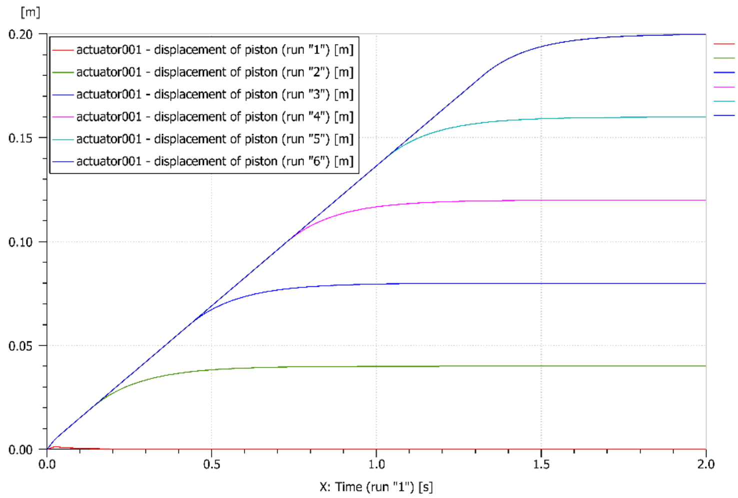


Fig.19. The response of the EHA for different step input signals

The simulation of the static and dynamic behavior of a theoretical actuator allowed the authors to design, build and test a small power actuator (Fig. 20) for pointing out the problems which can arise in a real compact design [18, 19]. The main challenge of the design was to find a small power bidirectional reversible gear pump with internal drain, and high-pressure shaft sealing. The next challenge was to find a brushless motor with analog or digital speed controller, delivering the torque and top speed needed to the pump. The pumping group, which includes the Panasonic servomotor [20], the Vivolo gear pump [21] and the HBM torque-speed transducer [22] is presented in Fig. 21. All the mechanical original components were manufactured by the Romanian aerospace company ICPEST. [23].

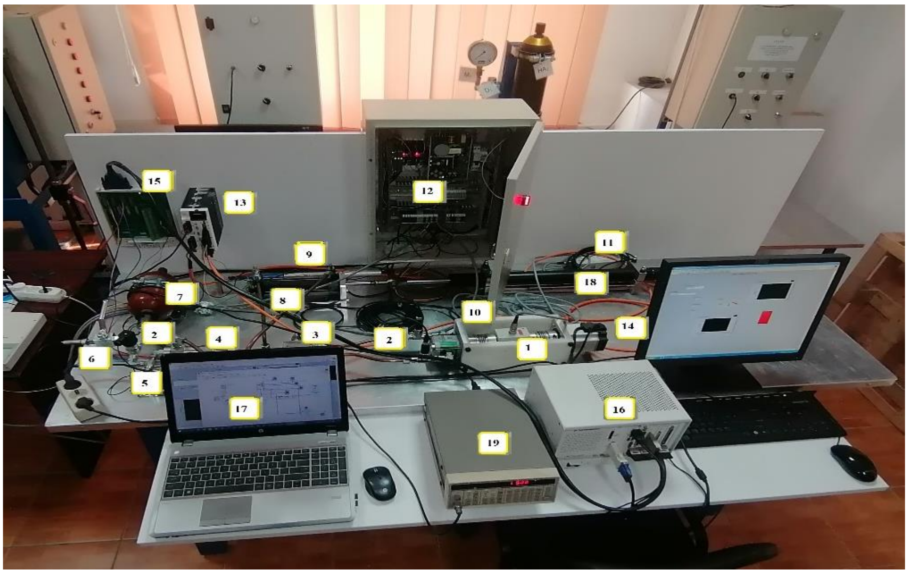


Fig. 20. Overall view of the test bench: 1 – gear pump with motor, torque-speed transducer; 2 – pressure transducers; 3 – block of pressure limiting valves; 4 – releasable directional valve; 5 – check valve; 6 – valve for charging the system with oil; 7 – hydropneumatic accumulator; 8 – hydraulic cylinder with mass and elastic load; 9 – position transducer; 10 – torque and speed adapter; 11 – interface of the torque and speed transducer; 12 – signal converters and power supply; 13 – brushless motor driver; 14 – brushless motor; 15 – AD interface; 16 – PXI digital controller for position loop; 17 – data acquisition system; 18 – mass and elastic load; 19 – functions generator.

Fig. 21. Pumping assembly including the pump, the servomotor and the torque-speed transducer.

A long series of experiments were performed in order to obtain a set of good performances by tuning the error amplifier of the position loop. However, some components feature generated short periods of noise and nonlinearities. The small stiffness of the spring load needs a small driving force. The aerospace mechanical sealings and external joins of the driving chain introduce some start delay, even if the load rod is sustained by linear ball bearings. The electrical noise introduced by different control system components were removed by digital filters. (Fig. 22). Both static and dynamic behavior were found in good agreement with the theoretical ones (Figs. 23 and 24).

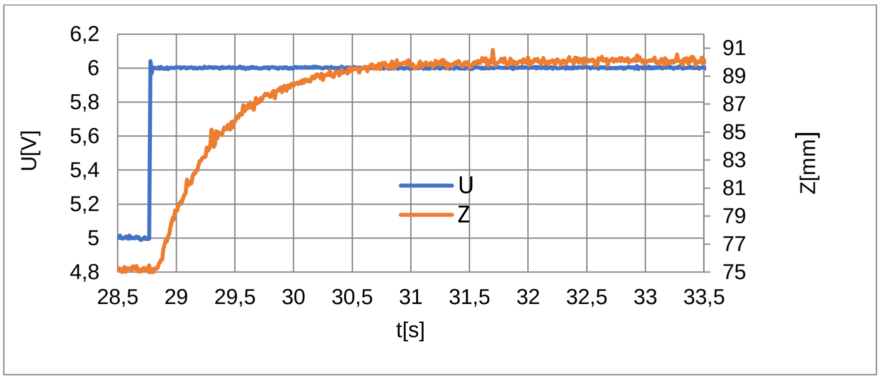


Fig. 22. Typical actuator response for a voltage step input, without digital filters.

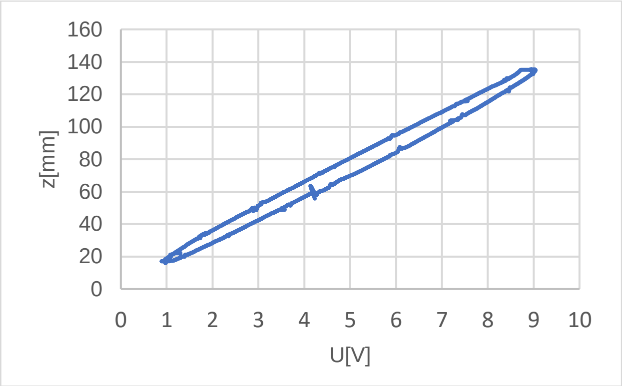


Fig. 23. Typical static characteristic of the actuator (unfiltered).

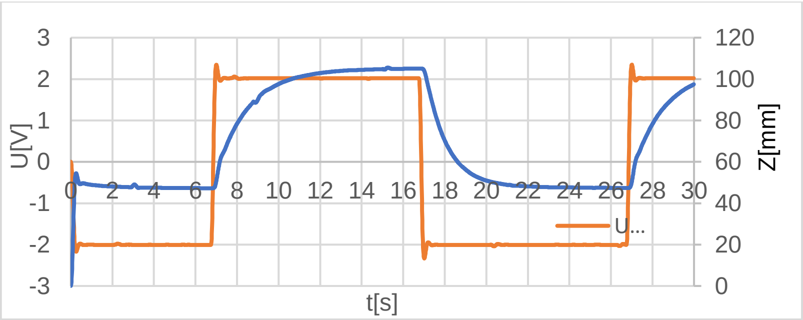


Fig. 24. The actuator's response to a series of rectangular voltage inputs.

Conclusions

The short research presented above regarding the great switch between the classical electrohydraulic servomechanisms and the hybrid ones leads to a unique conclusion: for small and medium power (up to 250 kW), the combination between a high-speed brushless motor electronically controlled, a compact bidirectional pump and a hydraulic cylinder represent the best choice for any kind of linear actuating, from aerospace flight control to CNC machines driving, autonomous trucks steering or subsea oil or gas pipes management. In good technical manufacturing and maintenance conditions, the overall energy consumption is strongly reduced (more than 40%), the needed space for setup is very small, and the average lifetime achieves 10,000 hours. The only important condition for keeping the initial performances is the use of very good quality materials and components.

The research team can now make a step ahead by design, manufacture and test of a general-purpose compact actuator, with wide applications in the new generation of mobile equipment, which is a great consumer of fossil fuel.

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