UNIVERSITY POLITEHNICA FROM BUCHAREST
ENERGY ENGINEERING DOCTORAL SCHOOL

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# DOCTORAL THESIS SUMMARY

## Researches for Improving the Efficiency of the Electrohydraulic Servomechanisms

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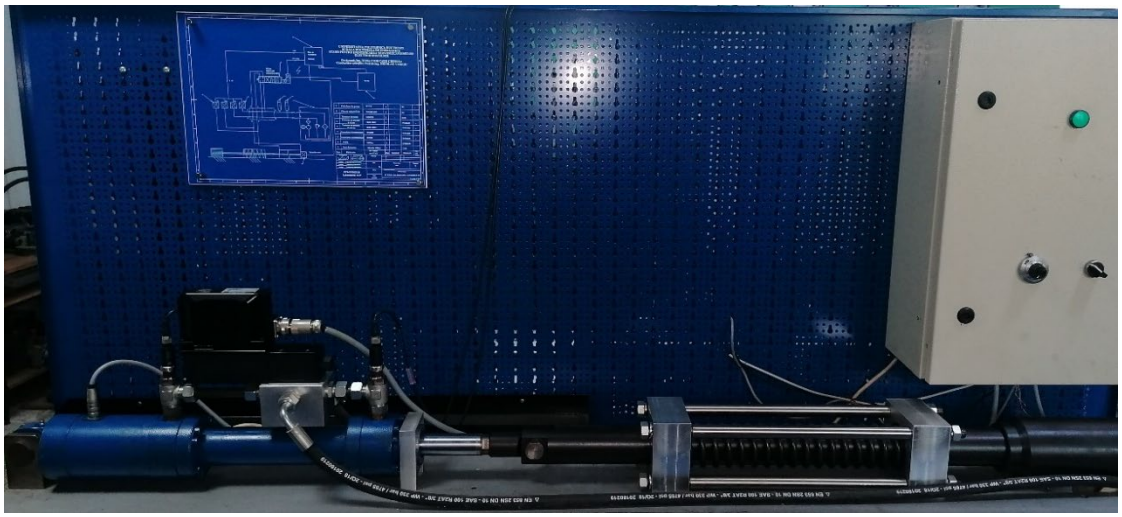

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# Content

**Thesis key words:** Energy Saving, Electrohydraulic Servomechanisms, Hybrid Servomechanism, Modeling, Simulation and Experimental Validation

## Synthesis of the main parts of the thesis

The exponential integration of brushless servomotors controlled by digital inverters in the most various applications with the usual level of electrical and electromagnetic protection has extended the field of use of medium power electromechanical servomechanisms to the field of classical electrohydraulic servomechanisms. The selection criteria between these two categories of complex automatic systems are numerous: static and dynamic performance required for the application, environmental conditions, the possibility of hierarchical management, qualification of maintenance personnel, compatibility with other servomechanisms in installations, etc.

The need to achieve significant forces with high efficiency has led to the emergence and rapid improvement of hybrid electrohydraulic servomechanisms, which maintain bidirectional hydraulic transmission, consisting of a constant capacity volumetric pump and a hydraulic cylinder, but the pump is driven by a brushless servomotor whose speed is adjusted according to the position error of the hydraulic cylinder piston. Thus, the efficiency of the hydraulic servomechanism increases considerably because this structure eliminates the major energy loss through the servovalve, and the dynamic performances of the system depend only on the power of the brushless servomotor and its time constant.

In this context, starting from the immediate requirements of the current economic fields of great interest, the author approached, with modern tools of systems theory, the conception, design, modeling, simulation and experimental identification of classical and hybrid electrohydraulic servomechanisms that are fundamental components of systems. for regulating energy equipment, flexible cell drive systems, industrial robots, presses and rolling mills of all types, as well as aircraft, ships, road vehicles, mobile equipment, remote control transport systems, etc.

The practical purpose of this thesis is to develop a unique design methodology for both types of drive systems that have in common the hydraulic power transmission between a constant capacity pump and a symmetrical or differential hydraulic cylinder.

In order to facilitate the integration of modern servovalves in complex digital automatic systems, the related mathematical models have been transformed into subroutines compatible with the analysis program by numerical simulation of AMESIM Simcenter technical systems (abbreviated - Amesim), considerably simplifying their optimal synthesis. The identification of the studied equipment and systems in the paper was made with interfaces for acquiring experimental data produced by NATIONAL INSTRUMENTS corporation from the USA, assisted by LabVIEW software package produced by the same company, as well as by other similar high-performance programs.

The paper summarizes the results of the author's long activity in the field of electrohydraulic servomechanisms in the Laboratory of Hydraulic and Pneumatic Fluid Power Systems of the Department of Hydraulics, Hydraulic Machines and Environmental Engineering of the Faculty of Energy of the POLITEHNICA UNIVERSITY of BUCHAREST. The laboratory is recognized by the Romanian Accreditation Association (RENAR) in the field of quality certification of electrohydraulic servomechanisms.

**The First Chapter** of the thesis is dedicated to the state of the art of research in the field of digitization of industrial electrohydraulic servomechanisms and their evolution to hybrid ones. The optimal combinations of these for different specific applications of great practical interest are also analyzed, such as the servomechanisms necessary for the autonomous driving of aircraft, trucks, mobile equipment, ships, etc. The documentation covers most of the established manufacturers of automatic electrohydraulic systems and indicates the natural tendency towards hybridization.

In the last three decades, all innovative companies have adopted numerical simulation with specialized software as a mandatory tool to accelerate the design of new complex automated systems. In the field of electrohydraulic servomechanisms, several complex languages of high efficiency in the field of optimal analysis and synthesis have been developed and validated. As a result, in **Chapter 2** the author undertook an objective analysis of the practical performance of the main widely used languages: SIMULINK, AUTOMATION STUDIO, AMESIM and LabVIEW.

In **Chapter 3** the author presents the conception, mathematical modeling, numerical simulation, design and testing of electrohydraulic servomechanisms with inertial elastic load necessary for a large number of applications of wide practical interest. Both the calculations and the experiments were performed with all three types of modern single-stage industrial servovalves, controlled by electromechanical converters with movable coil, proportional electromagnets or linear electromotors. For all these categories reached structural, technological and informational maturity, the author analyzed the results of the experimental identification of static and dynamic performances.

The servomechanism was realized by the Fine Mechanics Company ICPEST Ltd. and was tested in the U.P.B. Hydraulic and Pneumatic Fluid Power Systems Laboratory. The good results thus obtained were capitalized in a complex research-innovation project, necessary to promote "smart" agriculture - Platform for identifying the chemical composition of arable land, developed under the coordination of the National Institute of Agricultural Machinery (I.N.M.A.) and the Department of Technology Electronics and Reliability of the U.P.B. The interdisciplinary research project was funded by M.E.C. through the national plan under code 41PCCDI / 2018-2021. The servomechanism was reconfigured to be installed on the platform and successfully tested on the agricultural land of the mentioned institute. Thus, the capacity of its real tracking for random conditions of use (forces and speeds) was also verified.

Regarding the theoretical and experimental study of high-performance hybrid electrohydraulic servomechanisms, in **Chapter 4** the author studied the experimental identification of brushless electric motors, starting from their structure and specific drivers. The results of the experimental determination of the frequency response of a typical motor confirm the performance of the latest generation motors.

An important part of the thesis (**Chapters 5 and 6**) is dedicated to the modeling and numerical simulation of the dynamics of hybrid electrohydraulic servomechanisms. The author studied the modern structures developed in the last three decades for both aeronautical applications and those dedicated to fully robotic manufacturing. The study also includes the analysis of hybrid solutions introduced in the last decade for autonomous driving of heavy trucks produced by VOLVO, as well as US-patented hybrid solutions for military mobile applications.

**Chapter 7** is devoted to the structure, operation and construction of the experimental model of a servo controller dedicated to hybrid power steering. Its synthesis is performed by numerical simulation with LabVIEW language. The controller solution is original, being the subject of a patent application.

**Chapter 8** is dedicated to the construction, operation, tuning of functional parameters and presentation of the main results of the type tests of the hybrid electrohydraulic servomechanism performed in the thesis. The performance obtained, in accordance with internationally established regulations, indicates the definite possibility of using the concept proposed by the author to make the prototype for a large family of road vehicles and mobile equipment.

**Chapter 9** presents the synthesis of the author's original contributions to solving the approached topic. The author has published or communicated at prestigious scientific events written numerous articles and studies. Their synthesis is presented in the last chapter of the thesis.

## Synthesis of the author's scientific and technical contributions

Conceptually, this doctoral thesis promotes the fourth industrial revolution (Industry 4.0) because it is oriented towards the continuous automation of traditional industrial processes using information technology for digital management with maximum efficiency of all types of mechanisms and servomechanisms.

From a practical point of view, the author focuses on achieving a major energy saving obtained by eliminating linear and local load losses specific to classical hydraulic and electrohydraulic servomechanisms. The simultaneous launch, in 2006, of the most modern civilian (A380) and military (F35) aircraft revealed the trend of progressive replacement of servovalves, high energy consuming and sensitive to contaminants, with constant capacity servo pumps, driven by electric servomotors without brushes, controlled by digital inverters. This combination has become possible due to the improvement of electric motors with permanent lanthanide magnets and the increase of the power of inverters with transistors and thyristors.

The author of the thesis comparatively studied the issue of both types of servomechanisms in the first chapter of the paper based on a recent extensive documentation, which includes all types of information available, from press releases of major aeronautical and industrial equipment manufacturers to the latest presentations at prestigious conferences and magazines. The complete list of bibliographic references exceeds 200 titles dated after the year 2000. Thus, the synthesis elaborated by the author has already been published by IntechOPEN publishing house in 2020, being consulted by a large number of researchers in the field. The

volume entitled **"Hybrid Steering Systems for Automotive Application"** was edited by Luigi Cocco, PhD, the technical director of MASERATI, with the name "Advanced Applications of Hydrogen and Engineering Systems in the Automotive Industry". The mentioned chapter was consulted by a considerable number of specialists, attesting its originality.

The main calculation tool used in the thesis for the analysis of the dynamic and energetic performances of the classical and hybrid electrohydraulic servomechanisms designed and realized during the doctoral internship was the numerical simulation with general or specialized software. In Chapter 2, the author undertook an in-depth study of the peculiarities of the high-level interactive language SIMULINK, which allows the direct use of MATLAB modules dedicated to the analysis and synthesis of automated systems, as well as the export of programs in real-time controllers such as dSPACE. The valences of this language are theoretically and experimentally illustrated by a characteristic example of electrohydraulic servomechanisms with rotary motors used in the steering systems of remote controlled mobile machines.

The author briefly presented the valences of the AUTOMATION STUDIO sofware, widely used in the design of automatic electrohydraulic and electropneumatic systems made of standardized components. The main advantage of this program is highlighted: the direct adjustment during the simulation of the types and dimensions of the components, essentially increasing the productivity of the design process.

The task assumed by the author of the thesis - the design of original servomechanisms, required a detailed analysis of how to use the Amesim program, using an example of major importance for the field of hydraulic drives: mathematical modeling and numerical simulation of the dynamics of an adjustable axial piston swash plate pump.

All recordings of transient phenomena in newly designed electrohydraulic systems in the thesis were performed with LabVIEW program, which allows both numerical simulation and process management of automated systems of any kind. LabVIEW has an extremely wide field of application, with process modeling, simulation and control being only a part of the possible applications. The author also studied the basics of real-time process simulation with the LabVIEW program, which offers the possibility of running applications on a compatible platform equipped with a real-time operating system such as PXI or dSPACE.

Chapter 3 meets the requirements of a national project for mapping the properties of soils in our country using a towed platform, equipped with a system for measuring pH at different depths and an optoelectronic system for identifying the chemical composition of the soil. The author was part of the interdisciplinary team led by the National Research and Development Institute for Machinery and Installations for Agriculture and Food Industry - INMA Bucharest. The author of the thesis participated in establishing the principle and constructive solution of an electrohydraulic servomechanism made with industrial servovalves, elaborated the mathematical model, performed the parametric optimization of the controller by numerical simulation with the Amesim program. Subsequently, the author participated in the design and implementation of the servomechanism by the Society of Aerospace Mechanics ICPEST and the test stand for the laboratory of Fluid Power Systems to the U.P.B. Following, the author of the thesis participated in the installation of the servomechanism on the platform executed by the mentioned institute and, in its successful testing on the agricultural land of the I.N.M.A. The performance of the servomechanism is at the same level with the similar equipment cited in the literature, validating all stages of design, execution, testing and implementation on the platform.

**Chapter 4** of the thesis prepares from a practical point of view the study of hybrid servomechanisms developed in the second part of the thesis by experimental identification of brushless electric motors used in the construction of hybrid servomechanisms. After a brief analysis of the structure of brushless motors, the author presents the results of the experimental

determination of the frequency response of brushless servomotors and related drivers. The determination of the transfer function of a typical servomotor was performed by exciting it in frequency and processing the results with the MATLAB program. The results obtained coincide with those available in the literature.

Hybrid servomechanisms made with symmetrical hydraulic cylinders are modeled and studied from a dynamic point of view in **Chapter 5**. The results obtained by numerical simulation with the Amesim program coincide with those published by advanced companies in the field.

The author also studied the case of great practical interest of hybrid servomechanisms made with asymmetric hydraulic cylinders (**Chapter 6**). The difference in the active areas of the piston required the introduction in the hydraulic scheme of a 3-way direction valve, the dynamics of which is decisive for the precision of adjusting the position of the piston of the hydraulic cylinder.

In preparing experimental research on the performance of hybrid servomechanisms, the author participated in the design, execution and testing of a microcontroller dedicated to this type of system, presented in **Chapter 7**. The functional model was developed with the support of the Romanian branch of the US MICROCHIP. The tests validated the principle scheme and the possibility to grant the controller for various mechanical and hydraulic parameters of the components.

To study the performance of asymmetric hybrid servomechanisms, the author designed a complex stand executed by the same mechanical processing company. The stand was assembled in the laboratory by Fluid Power Systems to the U.P.B. Preliminary results, corresponding to step signals of different amplitudes, validated the numerical simulations in the previous chapter.

Experimental research has revealed the high efficiency of this type of servomechanism, which is applied at an accelerated pace by prestigious companies in the field in all types of industrial equipment, aeronautics and especially in industrial robotics.

The original theoretical and experimental results of the thesis allowed the author to publish numerous papers in journals and at international conferences.

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