R E P I E N S I O N

of a dissertation
for the acquisition of the educational and scientific degree "Doctor"

Field of higher education: 5. Technical Sciences
Professional field: 5.1 Mechanical Engineering
PhD program: Hydraulic and pneumatic drive systems

Author of the dissertation work: **M.Eng. Docho Svetlozarov Dimitrov**

Topic of the dissertation work: **RESEARCH OF DYNAMIC PROCESSES IN THE CONTROL OF PNEUMATIC MOTORS USING PULSE-WIDTH MODULATION**

Reviewer: Professor Gencho Stoykov Popov, Ph.D.
University of Ruse

1. Relevance of the Problem Addressed in the Dissertation Thesis

Electropneumatic positioning systems are widely used in various fields of engineering. Increasingly widespread application in automated pneumatic drive systems is found in systems employing high-speed solenoid valves, where control is often implemented through pulse-width modulation (PWM). Such systems are characterized by lower cost while fulfilling requirements that are typically achieved through the use of proportional valves. At the same time, they exhibit specific dynamic processes associated with valve characteristics, air compression, and the nonlinear properties of pneumatic components.

There is considerable interest among many researchers in clarifying these specific features; however, there are still insufficiently clarified issues concerning the dynamic processes in the PWM control of pneumatic motors. In this regard, the investigations of the processes occurring in electropneumatic systems using high-speed 2/2 solenoid valves make the developed dissertation thesis highly relevant.

The obtained results will contribute to the improvement of modeling studies and control methods for such systems, as well as to the development of more efficient and energy-optimized pneumatic drives.

2. Review of the Cited Literature

In the development of the dissertation thesis, the author has cited 140 literature sources. The majority of these sources are from the last decade and reflect the current state of research in the field of automated pneumatic drive systems. A very positive impression is made by the fact that the doctoral candidate has cited a significant number of studies related to the investigation of hydraulic and pneumatic systems conducted within the main scientific unit – the Department of Energy Engineering. This demonstrates that he is well acquainted with the research work of his colleagues, which enables him to utilize and further develop the achievements of the research team in this field.

In Chapter I, entitled “Analysis of the State of the Problem”, the doctoral candidate has

carried out a critical analysis of the literature sources used concerning the main issues of the research topic. The following aspects are included:

– Analysis of existing systems using proportional valves for control. It is shown that the most commonly used software package for this type of research is MATLAB-Simulink, while during prototype development and hardware simulation, a PD (Proportional-Derivative) controller with fuzzy logic (Fuzzy Logic Controller) is employed.

– Analysis of existing studies and mathematical investigations of pneumatic cylinder operation models. The equations included in the electropneumatic system model under isothermal conditions are presented.

– Analysis of existing models of drive systems with solenoid valves. High-speed electropneumatic 2/2 solenoid valves (ON/OFF) are examined through several system configurations, and the main differences between proportional valves and high-speed 2/2 (ON/OFF) valves are identified.

– Analysis of existing studies on pulse-width modulation (**PWM**) control and analog control. This analysis covers the broadest range of issues and is presented in the greatest detail, which fully corresponds to the objectives of the present research.

Additionally, this chapter analyzes studies related to the use of mathematical models for the flow rate passing through a 2/2 solenoid valve, as well as existing mathematical models of the flow characteristics of high-speed pneumatic valves. The specific features associated with the use of PID controllers in control systems, as well as fuzzy logic controllers, are also discussed.

All of the above clearly demonstrates that the doctoral candidate is thoroughly familiar with the characteristics, advantages, disadvantages, and insufficiently clarified problems associated with systems utilizing high-speed solenoid valves. This provides him with the opportunity to formulate the objective of the dissertation research and define the corresponding tasks arising from it.

3. Research Methodology

The research methodology is clearly defined and includes both theoretical and experimental investigations. It fully complies with the widely accepted structure of dissertation research in the field of mechanical engineering. The theoretical part includes the development of a flow characteristic model of a high-speed pneumatic 2/2 valve and a mathematical model of an electropneumatic positioning system with PWM control, where the MATLAB software package is extensively used.

The experimental investigations are related to studying the speed of a pneumatic cylinder using four high-speed 2/2 valves with PWM control and determining the static flow characteristics. The obtained results serve as a basis for simulating and verifying the mathematical model of the electropneumatic positioning system with PWM control of high-speed 2/2 valves.

In Chapter 2, a mathematical model of the flow characteristic of a high-speed 2/2 valve is presented. An experimental setup scheme is developed, and the methodology of the experimental study is described. The obtained results for the three investigated types of 2/2 valves are presented graphically: for the flow rate $Q_{kop} = f(p_{out} / p_{in})$ and for the flow coefficient. Here, it is recommended that the flow rate characteristics, similarly to the pressure

characteristics, be presented in a dimensionless form (for example, relative to a reference flow value for each pressure, or by another suitable approach). This would enable a more qualitative analysis of the experimental results and possibly the derivation of a generalized dependency.

Chapter 3 is devoted to the development of a mathematical model of an electropneumatic positioning system with PWM control. The equations of the individual components of a representative system of this type are described in detail, forming the overall system model. The model accounts for pressure variations in the compressor and receiver, the dynamics of high-speed 2/2 valves, hydraulic resistance forces in the pneumatic cylinder, as well as the dead volume at the end of the stroke (piston cushioning).

However, a schematic diagram of the investigated electropneumatic positioning system with PWM control is missing, in which the four high-speed valves are included. Therefore, the operational method described at the end of the chapter (Section 3.3) is not fully clear (it may refer to the diagram shown in the following chapter, Figure 4.1).

The method for controlling the speed of the pneumatic cylinder using high-speed 2/2 valves with PWM and for determining the static flow characteristics is studied in Chapter 4. This chapter presents results from experimental investigations carried out on a real system, as well as validation of the developed mathematical model of the electropneumatic positioning system. The components of the experimental test rig used for the experiments are described in detail.

A virtual instrument was developed in the LabVIEW environment, representing a control and measurement system for an electropneumatic positioning system implemented through pulse-width modulation of high-speed electropneumatic valves.

The results of the experimental investigations are presented graphically as time-dependent records of the measured variables. These include pressure, flow rate, piston displacement, and velocity variation as a function of time, for several PWM frequencies—20 Hz, 50 Hz, 70 Hz, and 100 Hz—and duty cycles ranging from 2% to 90%.

The dynamic characteristics of the investigated electropneumatic system under different test conditions are analyzed. The experimental results show a high degree of agreement with the mathematical model, which confirms its adequacy.

The final step of the dissertation research is the validation of the mathematical model of the electropneumatic positioning system using PWM control. This is performed through a comparative analysis between experimental and simulation results for different control signal amplitudes and duty cycles. The comparison is based on graphical representation of theoretical and experimental curves of the corresponding dependencies. The good agreement between both sets of results demonstrates the accuracy and applicability of the developed mathematical model of the electropneumatic positioning system using pulse-width modulation of high-speed 2/2 solenoid valves.

4. Contributions of the Dissertation Thesis

The contributions stated in the dissertation are classified as scientific-applied and applied, which I fully support. I consider that they adequately reflect the main results obtained in this research work. The contributions may be grouped into the following categories: proving with new means significant new aspects of already existing scientific fields, problems, theories,

and hypotheses, as well as obtaining confirmatory facts.

The following results can be identified as contributions of this dissertation research:

1. The developed mathematical models:

– for the flow characteristic of high-speed pneumatic 2/2 valves and the experimental verification of the model;

– of the high-speed 2/2 pneumatic valve;

– of the electropneumatic positioning system using pulse-width modulation of high-speed 2/2 solenoid valves.

2. The developed simulation models and obtained experimental results in the investigation of transient processes and dynamic characteristics of the studied electropneumatic positioning system with fast-acting valves and PWM control.

3. The developed automated measurement system for data acquisition, processing, and visualization of experimental data in static and dynamic studies of electropneumatic systems.

4. The developed experimental test rigs:

– for determining the static flow characteristics of high-speed pneumatic valves type SX12F manufactured by SMC;

– for investigating dynamic processes of an electropneumatic positioning system controlled by pulse-width modulation.

5. The proposed energy-efficient electronic unit for PWM control of high-speed pneumatic valves in electropneumatic systems.

6. The experimental validation of simulation results regarding the influence of the control signal frequency and duty cycle of the PWM signal on the dynamic characteristics of the electropneumatic positioning system.

5. Publications and Citations Related to the Dissertation Thesis

Five papers have been published based on the dissertation, one of which is authored independently by the doctoral candidate. These papers were presented at scientific conferences, with one of them being an international conference. The fact that they were published in the proceedings of various conferences in Bulgaria and abroad contributes to a wider dissemination of the conducted research among scientists in the field of hydraulic and pneumatic drive systems.

No information has been provided regarding citations of these publications by other authors.

6. Authorship of the Obtained Results

I am not personally acquainted with the doctoral candidate and do not have direct impressions of his work related to the development of the dissertation thesis. Therefore, I cannot form an adequate opinion regarding the authorship of the conducted research. However, I have very good impressions of the work of the research team in the field of Hydraulic and Pneumatic Drives at the Department of Energy Engineering of the Technical University of Gabrovo, and I can assume that the development of the dissertation thesis is primarily the result of the doctoral candidate M.Eng. Docho Dimitrov. Naturally, this has been achieved under the direct supervision of his scientific supervisor, Assoc. Prof. PhD Eng. Hristo Hristov, who is a well-known specialist among colleagues working in this scientific field. The

most accurate answer to this question can be given by the scientific supervisor and the members of the research unit in which the doctoral candidate was trained.

7. Abstract and Author's Summary

The abstract is prepared in a volume of 51 pages and is a rather extensive document. In practice, the main research results are presented almost in full, as in the dissertation itself, with reduced information mainly from Chapter 1. For this reason, the abstract largely overlaps with the dissertation text, which nevertheless ensures the availability of complete information regarding the conducted research and the obtained results.

8. Opinions, Recommendations and Remarks on the Dissertation Thesis

I was a reviewer at the internal defense of the doctoral candidate, M.Eng. Docho Dimitrov, and I pointed out certain remarks and recommendations. The majority of them have been taken into account in the final version of the dissertation. In Section 3, I also made some recommendations that could be considered in future research by the doctoral candidate.

I would like to allow myself to make several more general remarks:

– Chapter 1 is excessively large in volume (slightly more than 50 pages), and it contains information that is not further used in the subsequent chapters and has rather an informative character.

– In the study of the flow characteristics in Chapter 2 (and possibly in subsequent parts), the parameters of compressed air are referred to inlet conditions. I consider it more appropriate for them to be referred to so-called "standard conditions" — temperature 20°C, absolute pressure p = 101325 Pa, and relative humidity 50%.

– It would be good if, in the formulas where numerical values of certain coefficients are given (e.g., relation 3.50), an explanation is provided on how these coefficients are obtained, as well as the dimensions in which the other variables should be substituted. This is especially important since the list of symbols used in the dissertation, provided at the beginning, does not include units.

The above remarks and recommendations in no way diminish the achieved results. They are intended rather to improve future research by the doctoral candidate and the presentation of the obtained results.

9. Conclusion

A significant amount of research work has been carried out by the doctoral candidate. I am convinced that this has contributed both to his theoretical preparation and to the accumulation of experience in conducting precise experimental investigations. Mathematical models have been developed, and on their basis a number of simulation studies have been performed. Appropriate experimental test rigs have been designed, and the proposed mathematical models have been verified. An indisputable contribution is the large amount of experimental results obtained. All of this demonstrates that the formal requirements for a PhD dissertation in the field of Mechanical Engineering have been fully met — theoretical research through the development of mathematical (physical) models and experimental verification and refinement of these models.

I consider that the presented dissertation thesis meets the requirements of the Act on the Development of the Academic Staff in the Republic of Bulgaria. The achieved results give me grounds to propose that the **educational and scientific degree "Doctor" be awarded to**:

M.Eng. DOCHO SVETLOZAROV DIMITROV

in the field of higher education – 5. Technical Sciences,

professional field – 5.1 Mechanical Engineering.

29.05.2026 г.
Ruse

REVIEWER: .....

/prof. Gencho Popov, PhD/