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REVIEW

of the doctoral dissertation by mgr inż. Ahmed Zubair Jan , entitled

„*Method of efficient utilization of digital hydraulic concept in multisource hydrostatic drive systems*".

The supervisor of the doctoral thesis is: dr hab. inż. Krzysztof Kędzia

1. Legal basis for the review a doctoral dissertation

The legal basis for the review was a letter from the Mechanical Engineering Scientific Discipline Council of the Wrocław University of Technology (Chairman of the Mechanical Engineering Scientific Discipline Council of the Wrocław University of Technology, prof. dr hab. inż. Zbigniew Gronostajski) in Wrocław dated 22 May 2026 regarding the writing of a review of the doctoral dissertation, letter no. W10/RDND07/99/2026.

2. General characteristics of the doctoral dissertation

The doctoral dissertation is 202 pages long. The bibliography contains 110 items (without the author's articles), including articles and conference materials, textbooks, books, dissertations and guides. The table of contents is followed by a 2-page list of important symbols. The work is supplemented by numerous drawings (144 in the main part of the dissertation and 12 in the three appendices) and tables (7 in the main part of the dissertation and 51 in the three appendices). The substantive part consists of eight chapters and a summary with final conclusions.

The introduction, numbered as Chapter 1, briefly describes the history of the development of hydraulic drives from the 17th century to the present day, highlighting the key areas of technology in which the most significant changes in this field have taken place.

Chapter 2 provides a general overview of the concept of digital hydraulics, which is the main subject of this dissertation, highlighting its advantages compared to a conventional hydraulic drive system with a hydrostatic power unit featuring a variable-displacement axial-piston pump. Next, the general concept of this doctoral dissertation is discussed, which involves investigating the potential application of digital force hydraulics (DFP) solutions in multi-source hydrostatic drive systems to reduce energy consumption and maximize energy recovery through the recuperation process in hydrostatic systems. In the next section of the chapter, the thesis hypothesis was formulated, and five (5) main research problems—which constitute the objectives of the thesis—were defined in the form of questions. Finally, the subsequent subsections of the chapter describe the benefits the author expects from the planned research and analyses for the development of the scientific discipline, their significance in four (4) identified areas of hydraulic drive technology development, and briefly outline the generally planned research methods, divided into three (3) stages of the doctoral dissertation.

Chapter 3 contains a collection of general information on components used in power hydraulics, including digital hydraulics technology – hydraulic pumps, hydraulic actuators, valves, oil tanks, hoses (flexible pipes), pipes and pipe connectors. A mathematical model of a single hydraulic pump and hydraulic motor is presented. The structure of a hydraulic transmission and open and closed hydraulic drive systems (with open and closed loops) is then described. Finally, the technical limitations of traditional hydraulic drive systems are pointed out.

Chapter 4 introduces the concept of digital power hydraulics and discusses its main components. It characterizes the three main types of hydraulic valves used in digital hydraulics, including parallel valves with a digital flow control unit (DFCU), fast-switching valves, and step valves. It describes pulse-width modulation (PWM) techniques for digital control and the digital power management system (DHPMS). Finally, it compares conventional and digital hydraulic systems, highlighting their fundamental differences.

Chapter 5 begins with a discussion of the block diagram of a digital hydrostatic transmission simulation model, built in the MATLAB/Simulink environment using the Simscape Fluids library. The subsequent section describes the mathematical models representing the main components of the simulated digital hydraulic system, including: a digital pump assembly consisting of four gear pumps, hydraulic manifolds, check valves, a relief valve, and a hydraulic oil model describing its properties as a working fluid. Models of volumetric losses, as well as mechanical and hydraulic losses in the transmission and pressure losses in the hydraulic system's pipes, are described. Calculation models were formulated for energy efficiency, an ecological performance index, and for determining the environmental impact of the transmission under study, including emissions of toxic substances and noise. At the end of the chapter, general principles were formulated for conducting an extended economic analysis of the proposed digital hydraulic transmission in order to objectively compare its financial performance with that of existing conventional solutions.

Chapter 6 is devoted to describing the strategies for the planned simulation and experimental tests that were to be conducted in this study to evaluate and verify the performance of classical hydraulic systems and their counterparts implemented using digital hydrostatic technology.

The following Chapter 7 presents the results of laboratory tests on a digital hydrostatic transmission, which were conducted in collaboration with the INOE 2000 – IHP Institute for Hydraulic and Pneumatic Research in Bucharest, Romania. The experimental setup for the digital hydrostatic transmission is described. Next, the results of the laboratory tests of the digital transmission are presented in the form of a set of time-domain plots, under Test Scenario 1 for loads of 2.8 MPa, 5.7 MPa, and 10 MPa, under test scenario 2 for loads of 1.2 MPa and 6.0 MPa, and under test scenario 3 for loads of 1.2 MPa, 1.6 MPa, and 9.0 MPa. In each case, the measurement results for four technical parameters of the digital transmission were analyzed: flow rate (Q), pressure (p), torque (M), and active power (P) as a function of time. During the analysis, particular attention was paid to evaluating the repeatability of the measurement results and the overall stability of the experimental setup under investigation.

The final substantive and most extensive chapter of the dissertation (Chapter 8) presents the results of numerical simulations of a digital hydrostatic transmission. The first part of the chapter presents, in the form of graphs, the results of simulation studies of the digital hydraulic system conducted according to Test Scenarios 1, 2, and 3, for selected levels of constant transmission load pressure. Finally, the analysis was supplemented with additional studies of the digital transmission with a reduced operating cycle time of 10 s (Test Scenario 3a), 5 s (Test Scenario 3b), and the shortest cycle time of 2.5 s (Test Scenario 3c). Each test result, presented in graph form, was accompanied by a brief commentary, and at the end, all test results conducted according to the specified test scenarios were summarized in the form of conclusions.

The remainder of this chapter presents a simulation model of a classic open hydrostatic transmission, developed in the MATLAB/Simscape environment. This model was developed to create a basis for comparison in order to analyze and evaluate differences relative to a digital hydrostatic transmission. Experimental results and simulation calculations were compared for Test Scenarios 2, 3, 3a, 3b, and 3c for selected transmission loads. The set of graphs presented here allows for the verification of the simulation model through its direct comparison with data obtained from the physical prototype. The model's consistency with the actual prototype was analyzed and evaluated, identifying discrepancies and their causes. In the following section, a similar comparison was made of the test results for key operating parameters of the simulation model of a classical hydrostatic transmission and the model of a digital hydrostatic transmission. The purpose of this analysis was to assess the extent to which the digital transmission can replicate the operation of the classical system and to identify fundamental differences in their behavior, which was considered a key step in verifying the research hypothesis.

Based on the conclusions from the comparative analyses presented in the previous sections, it was assumed that the simulation models could be used for simulation studies at load pressures up to 20 MPa. The results of the simulation studies in this area are presented in the final section of the chapter, comparing models of conventional and digital hydrostatic transmissions for loads of 10, 15, and 20 MPa in Test Scenarios 3, 3a, 3b, and 3c, with load cycle times of 20, 10, 5, and 2.5 s. Each comparison of the test results for both transmission models is accompanied by a commentary.

The substantive section concludes with an extensive, 10-page summary containing the author's response to the five (5) issues—the theses presented in the dissertation—a proposal for replacing a conventional hydrostatic transmission with a digital one, and the final conclusions of the dissertation, along with a verification of the main research hypothesis.

The thesis is written in a clear and grammatically correct manner. The numerous figures, diagrams, and charts included in the thesis are clear and carefully prepared, making them a good complement to the content presented in the thesis.

3. Overall assessment of the thesis

The subject matter of the doctoral thesis submitted for review is relatively new, innovative and topical, especially with regard to the reduction of financial outlays necessary for the implementation of hydrostatic drive systems, including variable displacement pump units. The excessively high purchase price of variable-capacity hydrostatic pumps, especially axial piston pumps, which are the most popular in conventional drive technology, remains a significant problem that hinders the development of modern hydrostatic drive systems, limiting their use in many fields of technology, such as ocean engineering. On the other hand, the above-mentioned axial piston displacement hydrostatic pumps are very sensitive to contamination of the working medium – hydraulic oil – and are very troublesome to repair, requiring specialised competent service and equipment. This is very troublesome on autonomous vessels such as seagoing ships, where the responsibility for repairs on board a ship at sea usually falls on the ship's crew, who are often unprepared for this in terms of knowledge and competence.

The digital hydraulic pump units described in this paper, based on the use of positive displacement gear pumps, are less sensitive to oil contamination, relatively easy to repair, and their components are significantly less expensive than those of the axial piston hydrostatic pump units discussed. No special service is required for their repair, and often the ship's crew can do it themselves. Therefore, the development of science and the training of our own specialists in this field is very important and significant for the national economy, and I consider the topic to be relevant for the development of the scientific discipline represented.

The scientific objective of the doctoral dissertation was to develop a simulation model of an exemplary digital hydrostatic transmission with a power unit consisting of four positive displacement gear pumps of different nominal sizes, its experimental verification of technical properties for six selected test scenarios through laboratory testing, and a comparison of its selected technical properties to a simulation model of a classic hydrostatic transmission based on the results of numerical calculations.

To this end, the author first developed his own computational program in the form of a simulation model of a digital hydrostatic transmission, built in the MATLAB/Simulink environment using the Simscape Fluids library, while describing the mathematical models of the main components of the simulated digital system, including: a digital pump assembly consisting of four gear pumps, hydraulic distributors, check valves, a relief valve, and a hydraulic oil model describing its properties as a working fluid. He then formulated computational models for energy efficiency, environmental performance, and productivity metrics, as well as for determining the environmental impact of the transmission under study, including emissions of toxic substances and noise. At the end of the chapter, he formulated general principles for conducting an extended economic analysis of the proposed digital hydraulic transmission in order to objectively compare its financial performance with that of existing conventional solutions. In the following section, the doctoral candidate described the strategies for the planned simulation and experimental tests that were to be conducted in the study to evaluate and verify the technical properties of classical hydraulic systems and their counterparts based on digital hydrostatic technology. As a result, he developed six (6) different test scenarios (Test Scenarios No. 1, 2, 3, 3a, 3b, and 3c). In the next section of the dissertation, the author presented the results of experimental studies of a digital hydrostatic transmission for three scenarios, which were conducted in collaboration with the INOE 2000 – IHP Institute for Hydraulic and Pneumatic Research in Bucharest, Romania. In the final substantive section of the dissertation, the author presented the results of studies on selected technical and numerical properties of the digital hydrostatic transmission according to the six scenarios described earlier, under various load conditions. In the following section, the author presented a simulation model of a classic, open hydrostatic transmission, built in the MATLAB/Simscape environment. This model was developed to create a benchmark for analyzing and evaluating the properties of the digital hydrostatic transmission. Experimental results and simulation calculations were compared for Test Scenario 2 at transmission loads of 1.2 and 6.0 MPa. The set of graphs presented enabled the author to partially verify the simulation model by directly comparing it with data obtained from the physical prototype. The model's consistency with the real-world prototype was analyzed and evaluated, identifying discrepancies and their causes. Finally, a similar comparison was made of the test results for key operating parameters between the simulation model of a classic hydrostatic transmission and the model of a digital hydrostatic transmission.

The purpose of this analysis was to assess the extent to which a hydrostatic digital transmission can replicate the operation of a conventional system, as well as to identify the fundamental differences in their behavior—which was considered a key step in verifying the research hypothesis. A comparative analysis was also conducted regarding the financial implications associated with the construction and operation of a digital transmission and its conventional counterpart, using the previously defined concepts of capital expenditures (CAPEX), operating expenses (OPEX), and total cost of ownership (TCO).

I consider the main original achievements of the author of the reviewed work, Ahmed Zubair Jan, MSc, to be:

Osiągniecia naukowo-badawcze:

1. Construction of an appropriate laboratory stand for testing the technical properties of a digital hydraulic transmission.
2. Conducting experimental bench tests, including comparison and verification of its technical properties with a theoretical mathematical and simulation model of the transmission.

3. Developing a simulation model of a digital hydrostatic transmission, built in the MATLAB/Simulink environment using the Simscape Fluids library.
4. Conducting a series of numerical calculations and analyses using a simulation model of a digital hydrostatic transmission, built in the MATLAB/Simulink environment, in order to examine the technical properties of the tested transmission and partially compare and verify them with the results of experimental tests of a real transmission in a laboratory test bench.
5. Developing simulation models of classic and digital hydrostatic transmissions, conducting simulation tests for loads of 10, 15 and 20 MPa in order to compare the results of testing their technical properties with each other.

Praca ma charakter utylitarny, stanowiąc pomoc merytoryczną dla projektantów i eksploatatorów podobnych cyfrowych przekładni hydrostatycznych.

The main hypothesis of the dissertation, put forward by the author in chapter 2.2, has, in my opinion, been proven by the research, simulations and experiments carried out. All five (5) research questions (objectives of the work) posed in chapter 2.2 have been developed on the basis of the research and analyses carried out in the dissertation. It is worth emphasising the doctoral student's personal contribution to the experimental research, which in scientific studies such as doctoral dissertations is important and confirms the scientific and organisational and methodological competences of the doctoral student being assessed.

Critical remarks

1. The text of the dissertation—for example, in the introduction—lacks a clear and precise description of the distinction between the contributions of the author and those of the advisor. Given that the advisor has also worked on the topic of hydrostatic multi-source propulsion systems [11, 21, 42], such a clear and explicit description of this distinction would be helpful in unambiguously defining the doctoral candidate’s contribution to the reviewed thesis.
2. Chapter 7, in its description of the laboratory setup for the digital hydrostatic transmission, lacks a detailed characterization of the hydraulic drive components used in the experiments. Although the author of the dissertation provides the main technical parameters of the system components used in the experiments and numerical simulations in tabular form in Appendix C, he does not specify their exact types or manufacturers. In Chapter 9, “Summary,” Table 7 lists various pump manufacturers, but it is difficult to determine who specifically manufactures the gear pumps installed on the laboratory test bench. The appendix also lacks the inclusion of catalog data sheets for the components of the hydraulic system, particularly the gear pumps used. Furthermore, there is no presentation of graphs showing the energy efficiency of these pumps or their technical drawings with descriptions of compensating seals and other

seals, which may have a significant impact on the behavior of the pumps during dynamic phenomena associated with startup or braking processes.

3. The experimental tests of the digital hydrostatic transmission carried out in Chapter 7 were performed for test scenarios 1, 2 and 3, with the maximum operating pressure of the digital pump unit being only 10.0 MPa for Scenario 1, 6.0 MPa for scenario 2 and 9.0 MPa for scenario 3. Most of the tests were carried out at very low loads, i.e. for scenario 1 - 2.8 MPa and 5.7 MPa, for Scenario 2 - only 1.2 MPa, and at a load of only 1.2 and 1.6 MPa for Scenario 3. With such a low load on the digital pump unit, any design clearances of the individual gear pumps remained not completely eliminated and the elements of the side compensation seals were not completely fixed. The operation of the analysed gear pumps at full nominal load of 20.0 MPa may be different. Therefore, I consider the author's conclusions based on the testing of the digital pump unit only at low load pressures to be not entirely justified. I do not understand why the experimental digital pump unit was not tested at higher pressures, for example at a nominal pressure of 20.0 MPa , especially subsequent simulation studies based on a gear model implemented in the Matlab Simulink environment were carried out at higher pressures, i.e. at pressures of 10.0 – 20.0 MPa.

4. The simulation model of a digital hydrostatic transmission in the Matlab Simulink environment has been simplified to take into account only the dynamics of the working fluid. It does not take into account the actual dynamic parameters of positive displacement pumps, in particular their moment of inertia, the dynamic friction of the gears against the side compensation seals of the pump, or the phenomenon of damping. This may affect the accuracy of the simulation results obtained, especially the analysed pressure peaks that occur when individual sections of the digital power supply unit are switched on and off.

5. In section 8.2, the results of laboratory tests of the experimental digital gearbox were compared with the results of simulation calculations based on the use of a digital gearbox simulation model developed in the Matlab Simulink environment. Why were these comparisons made only for Scenario No. 2 and at such low gear operating pressures: 1.2 and 6.0 MPa? Why was no similar comparison made for Scenario No. 3 of the tests, especially at a load pressure of 9.0 MPa?

6. In section 8.3, a comparison was made between the characteristics of a classic hydrostatic transmission and its digital counterpart, obtained through simulation calculations of mathematical models of both transmissions developed in the Matlab Simulink environment. The comparison was made for transmission test scenarios No. 3 (20s), 3a (10s) and 3b (5s), but at a very low load – pressure of approx. 6.5 MPa. The above comparison was not performed for scenario 3c (2.5s), which is the most restrictive and may lead to greater inequalities in the behaviour of both analysed hydrostatic transmissions.

The critical remarks mentioned above are debatable and do not affect the positive assessment of the reviewed dissertation.

4. Specific comments

Below, I list the most significant editorial errors and mistakes noticed in the work.

1. Page 170, line 5 from the top, item [44] is: „ (…) with akumulation….” it should be: (…) z akumulacją ….”,

2. Many figures are illegible or difficult to read. For example: Figure 23, p. 41 (the elements in the diagram and the descriptions in the boxes are completely illegible—the figure should be enlarged to improve readability), Figure 28, p. 56 (the axis labels on the graphs are illegible) or Figure 65, p. 91 (the labels for the curves on the side of the graphs and the axis labels are difficult to read).

3. The description of the experimental setup in Figures 31, 32, and 33 on page 61 is insufficient. The figures should include labels for the individual components of the test setup (for example, P1–P4, DV1–DV4, HM, P5, PRV, RV, FM, PT1, PT2, etc.) with a description below the figures that would reliably correspond to the diagram in Figure 30/p. 58. All measurement points and sensors used in the bench tests should have been indicated in the photographs

4. No list of figures – this should normally be included at the end of the thesis after the bibliography.

The editorial specific comments mentioned above are of negligible importance for the positive assessment of the work.

5. Final conclusion

The work is interesting and informative. It demonstrates the author's great perseverance and independence in research, especially in the field of experimental research. An important advantage of the work is its utilitarian nature, which allows its results to be implemented in practice. The doctoral student has acquired the ability to conduct independent scientific research, analyse results and draw correct conclusions. In my overall assessment of the reviewed work, I conclude that the doctoral dissertation entitled „*Method of efficient utilization of digital hydraulic concept in multisource hydrostatic drive systems*", by mgr inż. Ahmed Zubair Jan meets the requirements set out in art. 187 ust. 1 i 2 ustawy z dnia 20 lipca 2018 r. *Prawo o szkolnictwie wyższym i nauce* (Dz. U. z 2024 r. poz. 1571) and may constitute the basis for him to apply for the degree of Doctor of Science in the discipline of 'Mechanical Engineering' . I therefore request that the dissertation be admitted for public defence.

[redacted]

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