

Review of two-line hydraulic drive research

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Abstract. The article provides a brief overview of literary sources from the PRC on the study of a hydraulic drive with two-line control. This hydraulic drive is a new electro-hydraulic system for regulating the flow of a positive displacement pump, developed on the basis of control systems for the electric motor and the volumetric displacement of an adjustable positive displacement pump. The hydraulic drive has two lines of control variables: the rotational speed of the drive motor shaft and the adjustable displacement of the pump. The composite function of the two control lines allows you to create a hydraulic actuator with high efficiency and operating speed. An advanced hydraulic drive with two-line control increases the overall natural frequency of the entire system.

Introduction

The proposed review is based on 10 scientific and technical articles of 3 scientific research organizations and 3 Chinese universities, published over the past 10 years.

The hydraulic drive has a number of advantages such as high energy intensity, short response time, high positioning rigidity and convenient adjustment. These advantages of the hydraulic drive are confirmed by the widespread use in world technology for over a hundred years. However, relatively large energy losses, especially in the range of low speeds (low efficiency), limit the further use of hydraulic systems including at high power. The application experience shows that the useful output power of the hydraulic system, especially the throttle control system, maximally amounts to no more than 20 ... 30% of the total input power of the system, and the rest of the energy is dissipated in the form of heat.

In the second half of the twentieth century, a hydraulic drive scheme was widely used, which included an asynchronous electric motor, a positive displacement pump with variable displacement using an electro-hydraulic mechanism that make up one control line, and a hydraulic motor. This hydraulic circuit is relatively simple in structure, relatively energy-saving and efficient, has a low cost of use and maintenance.

The flow rate of the positive displacement pump is determined by the product of the pump displacement V_{0H} and the rotational speed n of the pump shaft $Q = V_{0H}n$. [1] It can be seen that a displacement hydraulic drive in combination with an electric motor and a hydraulic pump with variable displacement can have two control lines with two variable parameters — the output motor shaft rotation speed and the pump displacement. It allows you to obtain an adjustable output (speed) characteristic of the hydraulic actuator according to two control variables simultaneously and separately, while the control actions of the two variables can cancel each other out. [2, 3] The proposed scheme involves increasing efficiency, higher positioning rigidity and other dynamic characteristics.



However, even at present, the second double-sided control line is most often used, which provides control of the speed of the output shaft of the hydraulic motor by changing the flow rate of the pump by changing the volumetric displacement.

Two-line hydraulic drive

A hydraulic drive with two-line control is a new type of hydraulic drive developed on the basis of a traditional line (first) for regulating the displacement of the pump and a line (second) for regulating the frequency of rotation of the motor shaft. [4, 5]

The principle of a hydraulic drive with two-line control is shown in Fig. 1. The electric motor drives a hydraulic adjustable pump. The controller in real time controls the output speed of the motor shaft (power unit) and the pump displacement, which ultimately controls the movement of the hydraulic motor. Changing the pump flow is carried out using a pump displacement control mechanism.

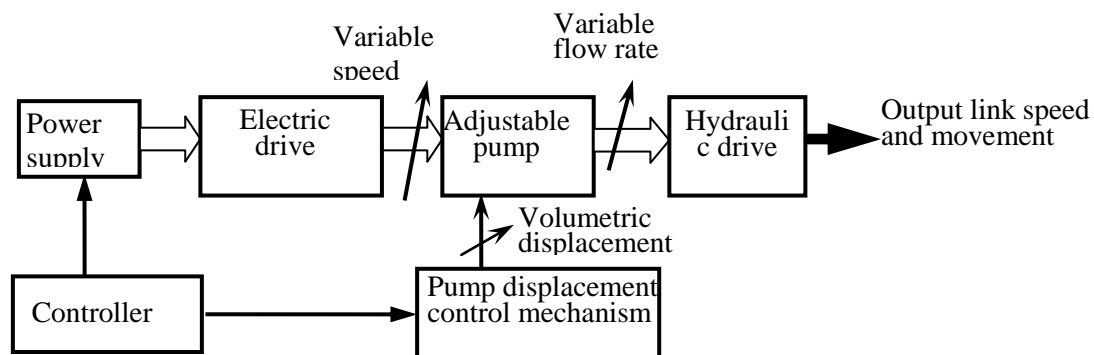


Fig.1. Schematic diagram of a hydraulic actuator with two-line control and two variable parameters

Schematic design of a hydraulic actuator with two-line control

In a hydraulic drive with two-line control (with two variable parameters), an axial piston pump with an adjustable displacement is used (Fig. 2). This type of hydraulic pump has a compact design, low moment of inertia, high working pressure and high volumetric efficiency. [6]

To ensure the accuracy of the pump supply, the vast majority of adjustable pumps use an electro-hydraulic mechanism with a proven circuit, for which the working fluid comes from the discharge line of a controlled pump or a specially equipped auxiliary pump. The block diagram of the electro-hydraulic mechanism is relatively complex. In addition, all this not only reduces the reliability of the entire control system, but also brings large energy losses during throttling of the flow of the working fluid in the electro-hydraulic mechanism. [7]

In order to improve the characteristics of the pump flow control mechanism, an electric drive mechanism was developed, shown in Fig. 2, which includes an electric motor and mechanical gear links.

The proposed scheme of the electric drive for regulating the pump displacement (the first control line) not only increases the performance parameters of the entire hydraulic actuator, but also facilitates integration and increases the level of integration of the control system with a computer system. For such a non-linear system, the difficult task arises - to conduct a relatively perfect simulation, analysis of modeling and research of the control strategy in full. The use of an electric drive eliminates energy losses during throttling of the working fluid flow in the electro-hydraulic mechanism, providing dynamic characteristics of the adjustable mechanism, which increases the energy efficiency and reliability of the executive system.

The use of a ball screw in an electric drive allows you to convert the rotational movement of the shaft into reciprocating motion of a nut that changes the angle θ_p of inclination of the support disk.

Since the dead zone of a ball screw is usually small, this suggests that the process of reversing movement will occur mainly without play (clearance), eliminates non-linearity in the dead zone during switching of the suction and discharge channels of the pump.

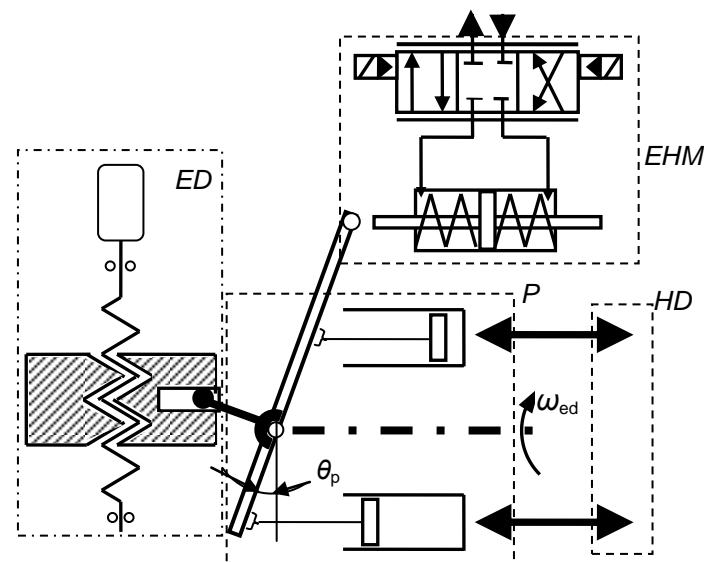


Fig. 2. Schematic diagram of a hydraulic drive with two-line control with two variable parameters; P — adjustable pump; EHM — electro-hydraulic mechanism; ED — electric drive; GD — hydraulic drive

The hydraulic drive with two-line control with two variable parameters there is no need for any switching components. [8] It is necessary not only to change the flow rate of the regulated pump, but also to achieve continuous adjustment of the operating system's gear ratio. The unique composite - compensation function - adjusting the shaft speed of the drive motor of this hydraulic drive and the control strategy of the pump displacement control mechanism can compensate for the defects and shortcomings of the hydraulic drive with a single source variable (regulating the pump flow rate only by changing the pump displacement), and it is expected that it will mainly solve the problem of reducing the energy consumption of the hydraulic drive. Solving the problem of reducing energy consumption and heating the working environment of the hydraulic drive significantly improves the dynamic characteristics of the executive system and further expands the bandwidth. It should be noted that the value of the product of the motor shaft rotation frequency and the volumetric displacement of the adjustable hydraulic pump determines the flow rate of the output flow entering the hydraulic motor. The same product allows you to determine the amount of power. The control effects of two variables can still compensate for each other.

It should be noted that a single-line hydraulic drive has typical non-linear characteristics. The dual control system has many non-linearities of its own, which complicates the nonlinear characteristics of a hydraulic drive with two-line control. For such a non-linear system, it is a difficult task to perform an ideal simulation, analyze the simulation, and study the control strategy.

Although the hydraulic drive with two-line control with two variable parameters has its advantages, consisting in convenient power transmission and simple control, it still has some differences from the traditional control system (with an electro-hydraulic mechanism) in the speed of operation and control accuracy. The proposed scheme of the electric drive for regulating the working volume of the pump (the first control line) not only increases the performance parameters of the entire hydraulic drive, but also facilitates integration and increases the level of integration of the control system with the computer system.

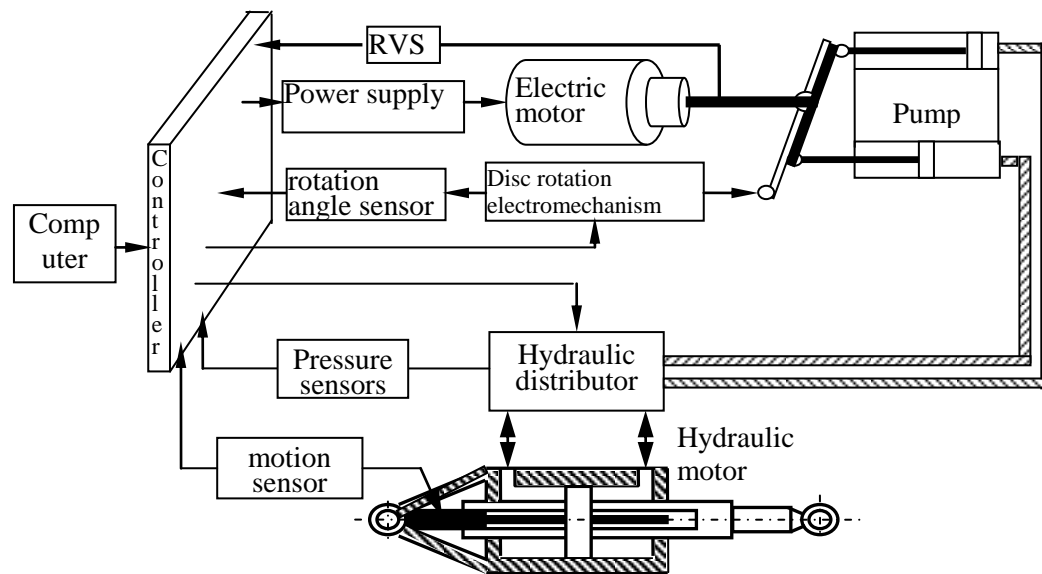


Fig.3. Schematic diagram of an improved hydraulic drive with two-line control

When introducing the second control line into the hydraulic drive (changing the motor shaft speed), it was found that in order to increase the controllability and the values of output characteristics, the pressure in the power discharge line must be increased, and the sum of the pressures in the high and low pressure hydraulic lines of the executive hydraulic motor must be maintained at a constant $p_{dis} + p_{suct} = 2p_{up}$. To ensure this mode of operation of the hydraulic drive, a hydraulic distributor was introduced into its structure, and an improved scheme is shown in Fig. 3. This brings the hydraulic drive with two-line control with two variable parameters in the operating state with a hydraulic drive with a single control line (electrohydraulic control), effectively forms the mechanical characteristic, increases the stiffness and improves the natural frequency and dynamic characteristics of the hydraulic drive. [8,9] The same effect is noted in the Russian sources [10, 11, 12].

During the research, it was noticed that when the feed values and pressures change in the hydraulic lines of the regulated pump, there is an improvement in the continuous adjustment of the transfer functions of the operating system. The unique composite (compensation function) - adjusting the shaft speed of the drive motor of this hydraulic drive and the control strategy — of the pump displacement control mechanism allows you to compensate for the shortcomings of the hydraulic drive with a single source variable (regulating the pump supply by changing the pump volume), and expect that these measures mainly solve the problem of reducing the energy consumption of the hydraulic drive. As a result, solving the problem of reducing energy consumption and heating the working environment of the hydraulic drive significantly improves the dynamic characteristics of the executive system and further expands the bandwidth. [13,14]

Thus, the existing literature mainly indicates the main direction of efforts to improve the structural scheme of the hydraulic drive with two-line control, including a new design of the electric drive mechanism that regulates the pump flow, and the improvement of the two-line control circuit.

Choosing a method for modeling the drive system

In a hydraulic drive with two-line control with two variables (the speed of the motor shaft and the working volume of the hydraulic pump), the parameters are multiplied in the working process and the value of the supply of the regulated pump is determined. At the same time, the hydraulic drive is affected by factors such as changes in the parameters of the hydraulic system, external load disturbances, and temperature changes. All this significantly complicates mathematical modeling and simulation analysis of a two-line hydraulic drive with two variable parameters. [15, 16] Currently, the

commonly used methods for modeling a hydraulic drive are the transfer function, state space, and connection graph methods. Among these methods, the transfer function method is the most common method of modeling in theoretical analysis. This method - often called the local linearization method - is used to work with internal change parameters in the simulation process and ignores some complex or difficult to describe model dynamics. The mathematical model obtained by this method is a model of linearization of the object of study.

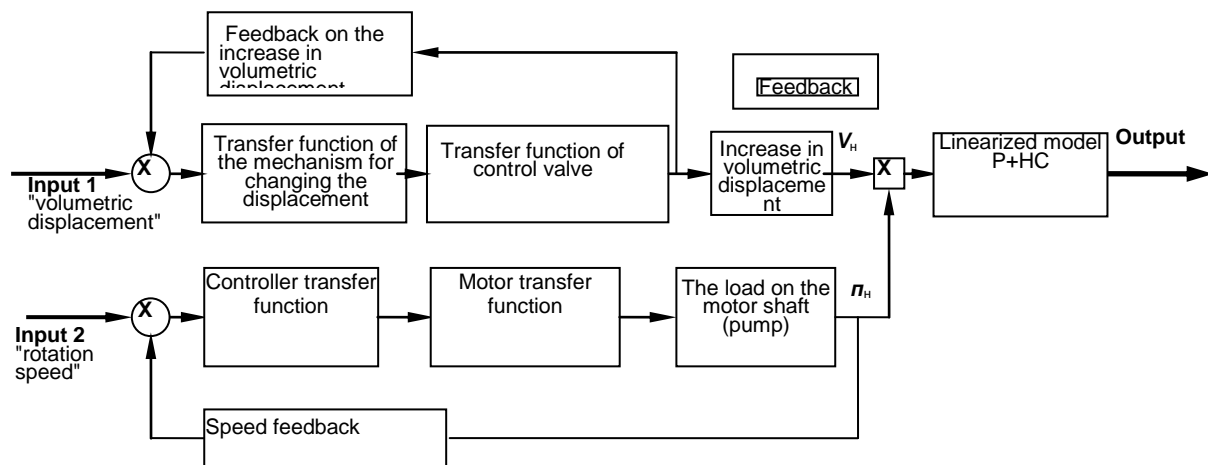


Fig. 4. Two-line hydraulic drive transfer function model

Based on the established linear mathematical model, it is convenient to use the classical control theory to analyze and design the executive system to achieve the required performance. The obtained model of the linearized transfer function of a hydraulic actuator with two-line control, shown in Fig. 4, is used to describe the operating characteristics of the control system.

Studies have established that the transfer function method is not completely suitable for a hydraulic actuator with two-line control with strong nonlinear connection.

The state space method is a widely used modeling method in modern control theory and is suitable not only for traditional systems with a linear constant with one input and one output, but also for non-stationary systems, nonlinear systems, and systems with several inputs and several outputs. When the state space method is used to describe the mathematical model of the object of study, it is no longer necessary to consider in detail non-linear characteristics, such as non-linearity, high order and their change in time, so this can effectively avoid the disadvantages of the modeling process of the transfer function method.

Using the idea of block modeling in the state space method in accordance with the working mechanism of each module, the corresponding differential equations are established and the differential equations of each module are integrated, a model of the state space of the hydraulic drive with two-system control is formed (Fig. 5) with a clear expression of the relationships between different state variables inside the system.

In fig. 5, the input quantities u_1, u_2 represent two control variables of a hydraulic actuator with two-line control with two variables, respectively. The state variables $x_1, x_2, x_3, \dots, x_{11}$ represent the rotational speed of the motor shaft at the input of the hydraulic pump shaft; rotation angle and angular speed of rotation of the motor shaft at the input of the displacement control mechanism (speed and displacement of the moving nut); angular velocity and angle of rotation of the inclined disk; acceleration, speed and movement of the hydraulic cylinder. Output y represents the movement of the output link of the hydraulic cylinder. The values $a_1, a_2, \dots, a_{13}, b_1, b_2$ and d_1, d_2 are the matrix of coefficients, the input matrix, and the parameters of the output matrix of the state space model, respectively.

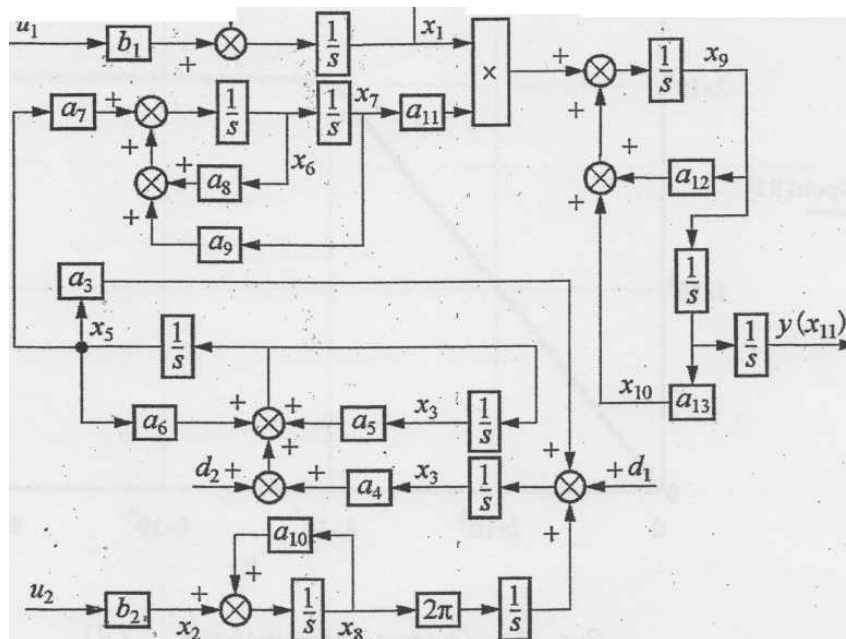


Fig. 5. Spatial model of the state of a hydraulic actuator with two-line control

The Bond graph method and co-simulation technology can take advantage of the simulation of various software platforms, simplify the modeling work, significantly increase the modeling efficiency and more accurately describe the performance of an electrostatic activation system with two variable parameters. This is a method of modeling and simulation with great development prospects. [17, 18]

Results and discussion

Thus, the reviewed literature gives a complete picture:

- of the determining directions of efforts of researchers of a hydraulic actuator with two-line control with two parameters;
- of improvement of the structural diagram of the hydraulic drive, including the new scheme and design of the electric drive mechanism that regulates the pump flow, and, accordingly, the improvement of the two-line control circuit;
- of the analysis of the main problems of improving the dynamic characteristics, energy efficiency and service life.

Conclusion

This hydraulic actuator is a new electro-hydraulic system developed on the basis of drive electric motor control systems and pump displacement control.

An advanced hydraulic actuator with two-line control increases the overall natural frequency of the entire system.

The composite function of the two control lines allows you to create a hydraulic drive that has the advantages of high energy efficiency and operational speed.

References

- [1] **O.F. Nikitin O.F., V.V. Yarots** Fundamentals of hydraulics and hydropneumatic drive, Moscow: Publishing house of BMSTU, 2019. — 490 p.
- [2] Review of research on dual-variable electro hydrostatic actuation system. **Feng Lijun, Yan Hao, Dong Lijing, Ren Yukai.** *Journal Beijing Jiatong University*. 2018, 42. №4, 104–112. (in Chinese)

- [3] **Krasovskii, A.B.** An analysis of the conditions for obtaining constant output power in a switched reluctance electric drive (2002) *Electrical Technology Russia*, 2002 (1)
- [4] Scheme analysis of power-by-wire airborne actuation systems. **QI Xiaoye, FU Yongling, WANG Zhanlin.** *Journal of Beijing University of Aeronautics and Astronautics*, 1999, 25(4):426–430. (in Chinese)
- [5] Research on dual-variable integrated electro hydrostatic actuator [J]. **GAO B, FU Y L, PEI Z C, et al.** *Chinese Journal of Aeronautics*, 2006, 19(1):77–82.
- [6] Modeling and AMESim simulation of electrohydraulic compound regulating integrated actuator [J]. **LANGYan, LI Yunhua.** *ActaAeronauticaEtAstronauticaSinica*, 2007, 28(S):152–157. (in Chinese)
- [7] The researches of state space modeling method and dynamic properties for double-variable electro hydraulic servo control system [D]. **LIU Erdong.** Xi'an: Xi'an University of Technology, 2015. (in Chinese)
- [8] Performance analysis based on AMESim and MATLAB co-simulation for dual-variable electro-hydrostatic actuator [J]. **JI Tieling, QI Haitao, LIU Zilong.** *Chinese Hydraulics & Pneumatics*, 2015(5):51–57. (in Chinese)
- [9] **Engineering. Encyclopedia.** T. IV-2. Electric drive. Hydro and vibro drives. In 2 vol. Vol. 2. Hydro and vibro drives. M.: Engineering, 2012. 304 p.;
- [10] Analysis and modeling of the multi-disciplinary coupling characteristics in EHA[C]//**LI K, WANG SP.** *International Conference on Fluid Power and Mechatronics. Beijing*, 2011:602–608.
- [11] **Vorontsov, A.L.** Theoretical aspects of technological mechanics: 1. Fundamentals of continuum mechanics (2013) *Russian Engineering Research*, 33 (4), pp. 206–210. DOI: 10.3103/S1068798X13040205
- [12] **Barmin, S, Nikitin O.F.** Definition of positive displacement output regulation mechanism parameters with providing of constant flow capacity in output. *IOP Conference Series: Materials Science and Engineering* 2019. — Vol. 589, Issue 1. — Art.no 012020 <https://iopscience.iop.or...57-899X/589/1/012020> DOI: 10.1088/1757-899X/589/1/012020
- [13] Motor speed robust control with multiplying nonlinear property [J]. **BAI Guochang, QI Xiaoye, WANG Zhanlin.** *Journal of Beijing University of Aeronautics and Astronautics*, 2008, 34(7):803–806. (in Chinese)
- [14] **Myagkov, L.L., Strizhov, E.E., Malastovskii, N.S.** Modeling of the thermal state of the diesel cylinder cover with allowance for liquid flow in the cooling cavity (2008) *Heat Transfer Research*, 39 (8), pp. 685–694. DOI: 10.1615/HeatTransRes.v39.i8.40
- [15] Multidisciplinary modeling method and simulation for electro-hydrostatic actuator [C]//**LI K, WANG SP.** 5th *IEEE Conference on Industrial Electronics and Applications. Taichung*, 2010:544–548.
- [16] **Krut'ko, P.D.** Robustly stable structures of control systems of high dynamic precision: Algorithms and dynamics of control of model objects (2005) *Journal of Computer and Systems Sciences International*, 44 (2), pp. 273–292.
- [17] **Medvedev, V.S., Romanova, T.A.** Synthesis of control algorithms providing independence of multidimensional plant subsystems (1995) *Izvestiya Akademii Nauk. TeoriyaiSistemyUpravleniya*, (1), pp. 54–71.
- [18] **Bychkov, M., Krasovsky, A.** Taking into Account Nonlinear Properties of Switched Reluctance Machines in Electric Drive Control Algorithms (2018) 2018 10th *International Conference on Electrical Power Drive Systems, ICEPDS 2018* — Conference Proceedings, № 8571868. DOI: 10.1109/ICEPDS.2018.8571868