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The Modelling and Simulation of the Control Valves in Hydraulic Systems

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Abstract

The paper describes the modeling of hydraulic systems associated to control systems that have the valve-type of execution element. The control systems with the control valves are complex structures because of the complexity of the construction of control valves and the hydraulic phenomena associated of the pumps and the pipes. The mathematic model of the control valve designed by the authors includes the model of the pressure source, the model of the transport pipe, the intrinsic characteristic and the operational characteristic of the regulation / control valve. The model's input is the command signal of the regulator and the model's output is the fluid flow rate which goes through the hydraulic system. A special focus is the mathematical model of the centrifugal pumps. The mathematic model proposed does not include relevant simplifying hypothesis, the solution being available only on the numerical way. The results obtained by using the proposed model have been compared with the classical solutions, determined on the basis of the simplifying hypothesis.

Key words: - *control valve, hydraulic system, pump, numerical solution*

Introduction

The modeling of control valves represents a delicate issue, because of the complexity of the mechanical construction of control valves, of the hydraulic phenomena and of the connection of the control valves with the other components of the control system, i.e. the controller and the process.

The fundamental element of the mathematical modeling of the regulation valve is represented by the operational characteristic of the regulation element [1, 3]. The solutions associated to the operational characteristic of the regulation element may be determined by inputting the simplifying hypothesis, which considers that the flow module associated to the pipe is not modified [2, 4].

In the present article, the authors have continue the developed the original model of the control valve presented in [6].

The Structure of Control Valves

The control valves are the most widespread execution elements in the field of chemical and petrochemical industry. In these cases, the control valve is considered a mono variable system, the input is the u command of the controller and the output is the manipulated variable m, associated to the process [5]. An industrial control valve consists of an electronic-pneumatic converter, a pneumatic actuator with membrane and a control element with a seat, fig. 1.

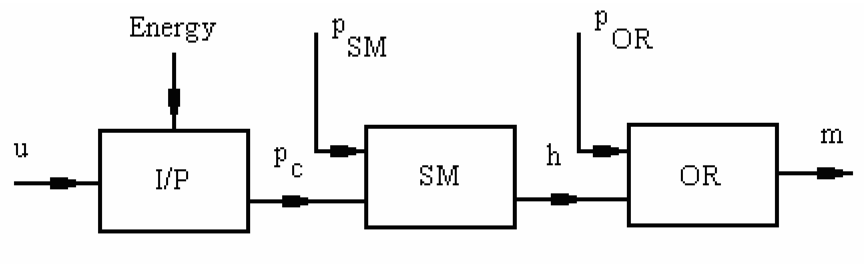

Fig. 1. The parts composing a valve-type execution element: *I/P* –electro-pneumatic converter; *SM* – actuator; *OR* – regulation element; *u* – command electrical signal; p_c – command pneumatic signal; *h* – the stroke of the servomotor; p_{SM} – perturbations associated to the actuator; p_{OR} – perturbations associated to the regulation element.

The Model of the Hydraulic System

There is a great variety from the point of view of structure of the hydraulic systems; they consist mainly of the pressure source, the transportation pipe and local hydraulic resistance, fig. 2. The structure of the hydraulic system and the phenomena occurring in it has a direct influence on the flow value when the controller commands the modification of the opening degree, respectively closing degree of the regulation valve.

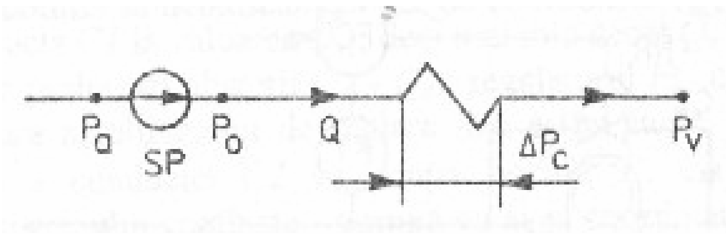

Fig. 2. The hydraulic system: P_a – aspiration pressure; P_0 – heading pressure; P_v – pressure at the end of the pipe; ΔP_c - pressure loss on the pipe; *Q* – flow.

The model of the pressure source

In the chemical and oil refining industry, they are used mainly centrifugal pumps operated at constant revolution. The mathematical model of the centrifugal pump may be approximated using the relationship

$$P = a_0 + a_1 Q + a_2 Q^2 + a_3 Q^3 \ . \qquad (1)$$

One of the research objectives of this project has been the determination of the statically characteristic of the centrifugal pumps. They have studying many characteristics pumps [7, 8, 9, 10, 11, 12]. In this paper, the authors have presented the statically characteristic of the MCS30 pump, figure 3. Using the polynomial regression method, the authors have determinate the numerical expression of the relation (1), associated to statically characteristic pumps MCS30. In the table 1 are presented the numerical values associated for the specifically AB 60Hz Oil pump. The figure 4 illustrates the correspondence between the experimental data and the regression function.

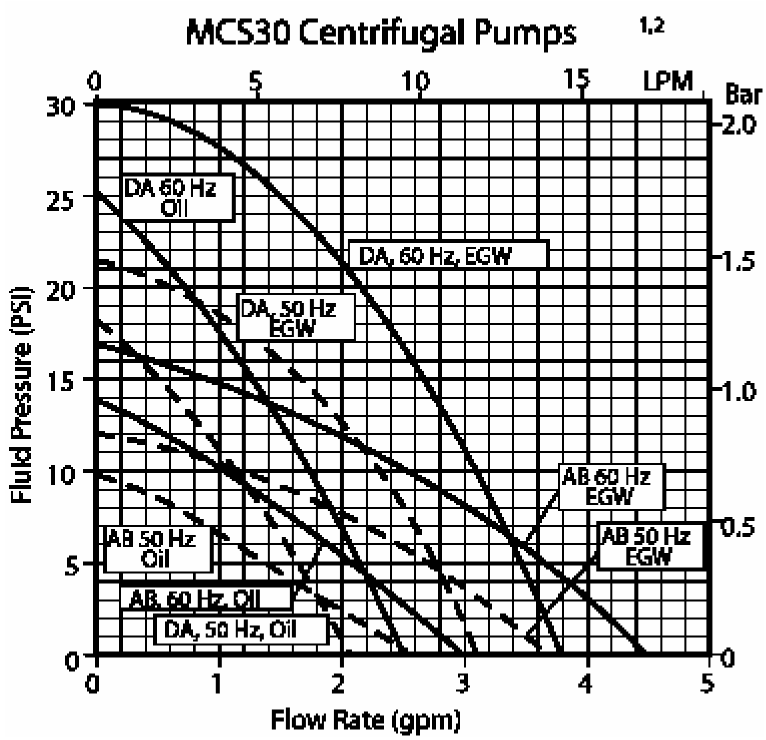

Fig. 3. The characteristics of the family MCS30 pumps

Table 1. Numerical coefficients associated to statically characteristic of the AB 60Hz Oil pump

Numerical degree of the polynomial function = 3
Standard deviation= 1.0501494E-0002
a0 = 9.4171755E-0001
a1 = -6.8758428E-0001
a2 = -8.3738007E-0001
a3 = 3.0171636E-0001

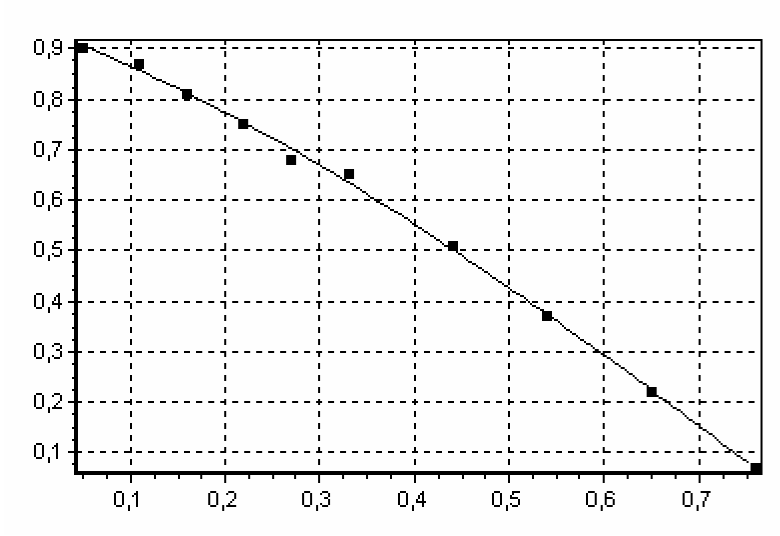

Fig. 4. The comparison between the experimental data and the regression function for the AB 60Hz Oil pump

The model of the pipe

The fluid transportation pipe represents a hydraulic resistance within the hydraulic system. The mathematical model for a straight pipe, with circular section, where the fluid flows in turbulently regime, is expressed by the pressure losses by friction

$$\Delta P_L = \lambda \frac{8L}{\pi^2 D^5} Q^2 \quad \left[\frac{N}{m^2}\right]. \tag{2}$$

where λ – friction coefficient; L – pipe length, in m; D – pipe diameter, in m; Q – volume flow of the fluid, in m^3/s.

The Model of the Control Valve

The control valve represents an especially hydraulic resistor, in witch the hydraulic resistance is modifying by the flow section and the flow conditions. The elements of the control valve model are the followings.

The intrinsic characteristic

The intrinsic characteristic represents a mathematical model of the regulation element which allows the establishing, in standard conditions, of hydraulic characteristics applying to the control valve, regardless of the hydraulic system where it will be installed. The intrinsic characteristic represents the dependence between the flow module of the regulation element and its stroke

$$K_v = f(h) \ , \tag{3}$$

where the flow module K_v represents a parameter introduced especially for the hydraulic characterization of control valves.

The flow module depends only on the characteristics of the regulation element, expressed depending on its opening, therefore by the h stroke of the valve shut – off. The intrinsic characteristic depend also on the geometrical construction of the regulation element (valve shut – off type with one seat, valve shut – off type with two seats, three-way valve shut – off type, corner valve shut – off type, flap valve shut – off type, spherical valve shut – off type). The mathematical models of the intrinsic characteristics are specific to every type of valve shut – off.

The most important mathematical models of the intrinsic characteristic associated to the valve shut – off type with one seat are named linear characteristic and logarithmical characteristic and are defined by:

- linear characteristic

$$\frac{Kv}{Kvs} = \frac{Kv_0}{Kvs} + \left(1 - \frac{Kv_0}{Kvs}\right)\frac{h}{h_{100}} \ ; \tag{4}$$

- logarithmical characteristic

$$\frac{Kv}{Kvs} = \frac{Kv_0}{Kvs} \ exp\left(\frac{h}{h_{100}} \ ln\frac{Kvs}{Kv_0}\right), \tag{5}$$

where h is the valve shut – off stroke versus the seat; H_{100} – the nominal value (maximum) of the valve shut – off stroke; K_{v0} – the value of K_v for $h = 0$; K_{vs} – the value of K_v at H_{100} nominal stroke.

The work characteristic

The work characteristic of the control element represents the dependency between the Q flow and the h stroke of the valve shut – off

$$Q = Q(h)\,. \qquad (6)$$

From the point of view of the hydraulic system, the operational characteristics may be associated to the following systems: systems without ramifications, hydraulic systems with ramifications, hydraulic systems with three-way valves, hydraulic systems which bypass the pressure source.
Because of the complex nature of these phenomena, for the mathematical modeling of the operational characteristic of the regulation element, the following simplifying hypotheses are introduced:

a) Only the case of incompressible fluids with a turbulent flow regime is treated;
b) Only the hydraulic systems without ramifications are modeled;
c) The pressure loss on the pipe is considered a concentrated quantity, under the form of a local hydraulic resistor.

The main scheme of a hydraulic system without ramifications is presented in fig. 5. The system is characterized by the loss of pressure on the regulation valve, ΔP_r, the pressure loss on the pipe, ΔP_C, and the loss of pressure inside the pressure source, ΔP_{SI}.

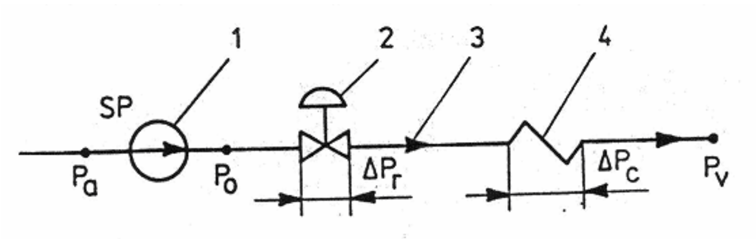

Fig. 5. Hydraulic system without ramifications:
1 – the pressure source; 2 – the regulation valve (RR);
3 – the pipe; *4* – the concentrated hydraulic resistance of the pipe

For the modeling of the operational characteristic of the regulation element, the following quantities are defined:

- the flow going through the regulation valve

$$Q = K_V \sqrt{\frac{\Delta P_r}{\rho}}\,; \qquad (7)$$

- the loss of pressure on the line, ΔP_L

$$\Delta P_L = \Delta P_C + \Delta P_{SI}\,; \qquad (8)$$

- the loss of pressure on the hydraulic system, ΔP_{S0}

$$\Delta P_{S0} = \Delta P_L + \Delta P_r\,. \qquad (9)$$

The control valve model

The authors have studied and elaborated a mathematical model of control valve. The model is based on the elements: the model of pump; the model of pipe; the work characteristic; the intrinsic characteristic and the energetic balance of the hydraulic system [8]. The model is defined by the block-scheme presented in fig. 6. Within the mathematical model, the input is the *h* stroke of the actuator and implicitly of the control element, and the output is the *Q* flow which goes through the valve.

The authors have developed a numerical solution of the control valve model. If the pump model is defined by a quadratic function, that the solution of the control valve model is a non-linear equation

$$a_q Q^2 + b_q Q + c_q = 0\,. \tag{10}$$

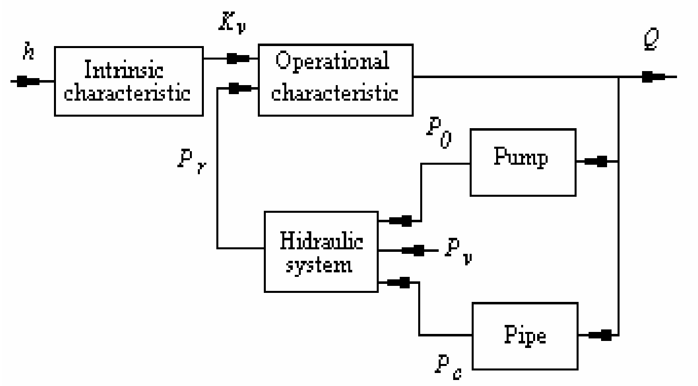

Fig. 6. The Model of the control valve

The coefficients of the equation (10) have the following expressions []:

$$a_q = a_2 \frac{K_v^2}{\rho} - b - 1\,; \tag{11}$$

$$b_q = a_1 \frac{K_v^2}{\rho}\,; \tag{12}$$

$$c_q = a_0 \frac{K_v^2}{\rho}\,. \tag{13}$$

Conclusions

The authors have development a new and original model for the hydraulic systems with the control valves. This mathematical model is especially made for the design and the check of the control valves, because the input data of hydraulic model is a variable of the control system.

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Modelarea şi simularea robinetelor de reglare în sisteme hidraulice

Rezumat

Lucrarea tratează modelarea sistemelor hidraulice echipate cu robinete de reglare. Sistemele de reglare care au robinete de reglare ca elemente de execuţie sunt caracterizate printr-o structură complexă, datorită atât complexităţii constructive a robinetelor de reglare cât şi a fenomenelor hidraulice asociate pompelor şi conductelor. Modelul matematic al robinetului de reglare include modelul sursei de presiune, modelul conductei, caracteristica intrinsecă şi de lucru a robinetului de reglare. Mărimea de intrare a modelului este semnalul de comandă elaborat de regulator şi mărimea de ieşire este debitul de fluid care trece prin sistemul hidraulic. O problemă specială a constituit-o modelul matematic al pompei centrifuge. Modelul matematic al robinetului de reglare, model propus de autori, nu include ipotezele simplificatoare clasice iar soluţia modelului nu poate fi determinată decât pe cale numerică. Rezultatele obţinute prin utilizarea modelului propus au fost comparate cu soluţiile clasice, determinate pe baza ipotezelor simplificatoare. .