Analysis of electromagnetic valve with spring at the joint of plunger and plug

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Abstract. Widespread use of electromagnetic valves in the engineering fields makes urgent the problems which are aimed to improve efficiency by optimization of their design. The paper aims to examine of efficiency of the electromagnetic valves with an accumulative spring at the joint in the kinematic chain with a plunger and a plug. To achieve the primary goal, the two problems are formulated and considered: analysis of the electromagnetic valve by considering its operation as separate phases; experimental investigation of the valves and comparison of electromagnetic characteristics of the valves having an accumulative spring with the same characteristics of classical electromagnetic valves. The design and principle of valves with an accumulative spring operation are considered. The dynamic equations of electromagnetic valves with an accumulative spring, which are took into account a pressure drop while the valve is opened, are stated. The equation for accumulative spring stiffness that is proportional to the given resistant force created by the pressure of fluid is written. The results of experimental investigation of the valves with an accumulative spring show that current in a coil is linear for all values of operating environment pressure. The power demand can be reduced by using an accumulative spring.

1. Introduction

A classical electromagnetic valve can be defined as a device in which movement of a plunger occurs due to electromagnetic forces and wherein the plunger is rigidly connected with a plug. Such valves are widely used in many engineering fields. In recent years, the electromagnetic valves are being used more and more in combustion engines instead of cam gears [1, 2]. Performance and operational reliability of the industrial systems with control valves are greatly affected by characteristics of these electromagnetic valves [1, 3]. Geometrical dimensions and energy consumption of an electromagnetic valve actuator are important characteristics in terms of the operational reliability and the performance both the valve itself and a control object. Therefore, optimization of the electromagnetic actuator of the direct acting valves for geometrical dimensions and energy consumption is an important problem.

Here are a lot of research papers in the field of electromagnetic valves optimization that are floating around applications of electromagnetic valves in different technical devices [1, 3, 4]. Moreover, the valve actuator, which is generally an electromagnet, is the aim of optimization. Today the growing interest in application of the electromagnetic actuator in mechatronics [5, 6] makes urgent the investigation of new approaches to design of electromagnetic actuators that have a lower weight of used material per unit work under given solenoid heating conditions [6]. Determination of the relation between electrical characteristics and geometrical parameters is an
important problem both in terms of finding engineering calculation techniques [4, 7, 8] and in terms of optimization of a design. There is approach to optimization providing a low power consumption without changing dimensions of the valve. It is based on application of accumulative springs in the kinematic chain with a plunger and a plug [9]. Such valves we will call electromagnetic valves with an accumulative spring.

2. Problem statement
The paper aims to analyze the an electromagnetic valve having an accumulative spring in the kinematic chain with the joint of a plunger and a plug. To achieve the primary goal, the following problems are formulated and considered:
1. Analysis of the electromagnetic valve by considering its operation as separate phases;
2. Experimental investigation of the valves. Comparison of electromagnetic characteristics of the valves having an accumulative spring with the same characteristics of classical electromagnetic valves.

2.1. Design analysis.
The basic scheme of classical electromagnetic valve and valve having accumulative spring consists of two parts (see Fig. 1) without regard to a design and over-all dimensions.
The first part is a valve. A valve body 5 has an inlet channel 10 and outlet channel 9 with a seat 8 which is overlapped by a plug 7. The plug 7 is provided with a return spring 6 and connected with a rod 4 which is linked to a plunger 3.
The second part is an electromagnet by which the valve is shifted to open position. The electromagnet comprises the magnetic core 1, a coil 2 and the plunger 3.
The electromagnetic valve having an accumulative spring has been changed in connection of the rod 4 and the plunger 3. The connection has linear elastic element – a spring. Generally, the accumulative spring can be in the form of any spring element efficiently storing deformation energy.
Fig. 1 shows the electromagnetic valve that differs from classical electromagnetic valve in containing of an accumulative spring 13, a bucket 11 and a tail stock 12 linked to the rod 4. The accumulative spring 13 is placed in the bucket 11 and set so that it encloses the rod 4. In addition, it rests at one end against the tail stock 12. The bucket 11 and the plunger 3 are connected rigidly.

**Figure 1.** Basic scheme of electromagnetic valve having accumulative spring: 1 - magnetic core; 2 - coil; 3 - plunger; 4 - rod; 5 - valve body; 6 - return spring; 7 - plug; 8 - seat; 9 - outlet channel; 10 - inlet channel; 11 - bucket; 12 - tail stock; 13 - accumulative spring.
Operation of classical electromagnetic valve is to supply current to the coil 2 for the valve to be opened, i.e. for the plug 7 to be moved (out) from the seat 8. Thus, electromagnetic force arises. The plunger 3 passes it to the plug 7 through the rod 4. Separation of the plug 7 from the seat 8 takes place when the electromagnetic force exceeds an external load (counter force) due to pressure of an overlapped area and of a return spring. Further, the plunger 3, the rod 4, and the plug 7 move to the magnetic core 1 by a value of plunger full stroke $x_{\text{max}}$. When current from the coil 2 is switched off, the plug 7 is set at the initial position and overlaps the seat 8 under influence of the return spring 6. Let us agree that the classical valve opening process occurs per one phase.

The opening process of the electromagnetic valve with an accumulative spring is accomplished in a few phases. Now we define these phases for design shown in Fig. 1.

With current supplied to the coil, electromagnetic force arises at the first phase. The force moves the plunger and the bucket by a value of the air gap $\delta_1$ between them (value of accumulative spring strain). At the same time, the electromagnet overcomes the elastic spring force of an accumulative spring. The accumulative spring accumulates potential energy of deformation under the action of electromagnetic force. The first phase ended at that point.

A plunger stroke attains value $\delta_2$ at the second phase when the maximum degree of accumulative spring deformation is reached. It results in significant growth of electromagnetic force that is sufficient to separate the plug 7 from the seat 8 and to open the valve. It is assumed that accumulative spring is in a compressed state. Distance between the plug and the seat, before the valve is fully opened, is less than given by a value of accumulative spring deformation. The second phase is ended at that point. At the third phase movement of the plug into the given position relatively to the seat is due to the process where potential energy of accumulative spring deformation converts to kinetic energy of the plug.

When current from the coil is switched off, the plunger returns to initial position under influence of the return spring and the plug overlaps the seat.

### 2.2. Experimental procedure.

Valves analysis is carried out for various designs of the electromagnetic valves by energizing valves at a different pressure of operating environment. Direct acting, normally closed valves – the classical electromagnetic valves with different valve flow area (II, III) and valves having an accumulative spring (I) – with technical characteristics presented in Table 1 were considered.

Electromagnets of the valves I and II are intended for valves having a seat with a diameter of 0.8 mm and pressure $24 \times 10^5$ Pa. The valve electromagnet III is for valve having seat with a diameter of 1 mm and pressure $54 \times 10^5$ Pa. The flow area of valves I, II and III are modified to a seat diameter of 9 mm, i.e. the valve design in all tests is identical with a seat diameter of 9 mm. Such seat diameter is not a nominal valve size for its electromagnet for all three valves.

The characteristics of the valve I and the valve II are the same. The connection of the plunger and the plug in the valve I has an accumulative spring, which is shown in Fig.1.

#### Table 1. Specifications of test specimens (electromagnetic valves)

| Electromagnet mass, kg | Coil resistance, ohm | Plunger diameter, mm | Diameter of valve flow area, mm | Plunger stroke, mm | DC voltage, V |
|------------------------|----------------------|----------------------|-------------------------------|-------------------|-------------|
|                         |                      |                      |                               |                   |             |
| With an accumulative spring I |                      |                      |                               |                   |             |
| 0.2                    | 75                   | 14                   | 9                             | 6                 | 27          |
| Classical II           |                      |                      |                               |                   |             |
| 0.2                    | 75                   | 14                   | 9                             | 6                 | 27          |
| Classical III          |                      |                      |                               |                   |             |
| 1.2                    | 50                   | 22                   | 9                             | 6                 | 27          |

In the first set of tests, a current level of electromagnetic valve I is compared with a current level of
the valve II at the moment when the valves are opening and pressure of operating environment is from \(2 \times 10^5\) Pa to \(10^6\) Pa.

In the second set of tests the valves I and III are compared.

Pressure of operating environment and valve response time are basic parameters.

Experimental equipment amounts to a testing workbench that has a compressor, a pneumatic pipeline, a manometer, fittings, the testing valves, wires, a DC source, an ammeter, and switches for current to be supplied from the DC source to a coil of the testing valves.

**Figure 2.** Experimental equipment.

Valve response time (from the moment of current supplying to a coil to the moment of the plug separation) was measured through observations from the time of pressing a current supply button to the time of the beginning of the plug movement.

### 3. Theory

#### 3.1. Plunger dynamic equation.

Let us consider dynamic of plunger for design in Fig. 1. There are following forces at the functioning plunger:

- inertial force which is produced by moving plunger mass;
- reaction force of operating environment that is proportional to a seat area \(S\) and to a pressure difference \(\Delta P\) between inlet and outlet channels;
- elastic spring forces of an accumulative spring and a return spring;
- dry friction force;
- viscous friction force.

Direct acting valves are characterized by the following equation

\[
m\ddot{x} = F - P_1S_1 + P_2S_2 - k_{rs}x - F_{0rs} - \alpha \dot{x} - \beta \text{sgn} \dot{x} \tag{1}
\]

where \(x\) – a plunger stroke; \(m\) – mass of moving parts; \(F\) – moving force; \(P_{1(2)}\) – inlet and outlet channels the pressure of fluid; \(S_{1(2)}\) – inlet and outlet areas; \(\alpha \dot{x}\) – viscous friction force; \(\beta \text{sgn} \dot{x}\) – dry friction force; \(k_{rs}\) – an elastic coefficient of a return spring; \(F_{0rs}\) – force created by initial set of a return spring.

Equation (1) of electromagnetic valve having an accumulative spring is written as follows taking into account pressure drop while the valve is being opened:

\[
m\ddot{x} = F_e + (P_1S_1 + P_2S_2)\rho(x) - k_{rs}x - F_{0rs} - k_{as}x - F_{0as} - \alpha \dot{x} - \beta \text{sgn} \dot{x},
\]

where \(F_e\) – electromagnetic force; \(k_{as}\) – an elastic coefficient of an accumulative spring, \(F_{0as}\) – force
created by initial set of an accumulative spring; \( \rho(x) \) – a function which takes into account pressure drop while the valve is being opened. When the function is equal to 1 – maximum value of the function – no pressure drop occurs and the system is in a state of equilibrium.

Following formula describes electromagnetic force [6]

\[
F_e = \frac{SN^2 \mu_r^2 \mu_0 I^2}{2(l_x + l_{eq} + (\mu_r - 1)x)^2},
\]

For the operating time of an electromagnet in different phases to be calculated we will use equation (2)

\[
mdv = [F_e + (-P_1 S_1 + P_2 S_2)\rho(x) - k_{rs} x - F_{0rs} - k_{as} x - F_{0as} - \alpha \dot{x} - \beta \text{sgn} \dot{x}]dt,
\]

where \( v \) – linear velocity.

Let us consider dynamic of electromagnet at the first phase for the classical electromagnetic valve and the valve having an accumulative spring after current supplying. Before electromagnet being activated, the plunger is at the standstill position due to resistant force caused by an environment pressure and a return spring. Moreover, velocity and acceleration components, dry friction force, and viscous friction force are equal to zero, while \( \rho(x) = 1 \). Using equation (2) for classical electromagnetic valve, we obtain equation of statics equilibrium:

\[
F_{el1} + (-P_1 S_1 + P_2 S_2) - F_{0rs} = 0,
\]

where \( F_{el1} = \frac{SN^2 \mu_r^2 \mu_0 I^2}{2(l_x + l_{eq} + (\mu_r - 1)x_{max})^2} \); \( x_{max} \) – maximum value of a plunger stroke.

Equation of statics equilibrium for electromagnetic valve having an accumulative spring can be written as:

\[
(-P_1 S_1 + P_2 S_2) - F_{0rs} \gg k_{as} x + F_{0as},
\]

where \( F_{el2} = \frac{SN^2 \mu_r^2 \mu_0 I^2}{2(l_x + l_{eq} + (\mu_r - 1)(x_{max} - \delta_s))} \).

Formula (3) means that motion of plunger starts from overcoming forces caused by the pressure of fluid and a return spring, while formula (4) shows that motion of plunger starts from overcoming forces created by an accumulative spring.

3.2. Accumulative spring stiffness.

Accumulative spring stiffness for given resistant force created by the pressure of fluid and for maximum degree of accumulative spring deformation \( \delta_s \), can be defined from (3) and (4) can be expressed as:

\[
(-P_1 S_1 + P_2 S_2) - F_{0rs} - k_{as} x - F_{0as} = 0.
\]

For \( x = \delta_s \), i.e. if valve is activated, accumulative spring stiffness can be written as:

\[
k_{as} = \frac{(-P_1 S_1 + P_2 S_2) - F_{0rs} - F_{0as}}{\delta_s}.
\]

4. The results of experiments

The first set of tests shows that the current in a coil for the classical electromagnetic valve II changes from 0.65 A to 1.6 A, however, it is not for all pressure values. When pressure was \( 1 \times 10^6 \) Pa the valve was not opened. The current in the valve I with an accumulative spring, which has operated for all pressure values, is equal to 0.4 A for any pressure.
The valve response time of the valve II for pressure $2 \cdot 10^5$ Pa is 0.36 s, for all other values of pressure the valve response time more than 8 s. The valve response time of the valve I changes from 0.16 s to 0.8 s in accordance with growth of pressure of operating environment.

The value of current in a coil for the classical electromagnetic valve III was defined at the second set of tests. The current changes from 0.3 A to 0.65 A. The valve response time of the valve III changes from 0.56 s to 1.44 s. Although, the valve response time was defined not for any pressure of operating environment.

A current change for the classical electromagnetic valves is linear for all values of operating environment pressure. Although, for the electromagnetic valves with an accumulative spring it is constant and equal to 0.4 A for all values of pressure. The valve response time increases with growth of pressure.

5. Discussion of the results
In the theoretical part of the article, the model of plunger movement for the valves having an accumulative spring is presented. The dynamic equation of the valves with an accumulative spring is different from classical ones by having phases in their operating. Separation of the phases is caused by nonlinearity of the valve operation that, in turn, is produced by moving mass changes. At the first phase it is a plunger mass, at the second one – masses of the plunger and the rod with the plug.

The refined model takes into account pressure drop when the valve is opened. It is necessary, since one must make allowance for a state of the system between the first and the second phases. Definition of an accumulative spring stiffness, considering that valve is operated, allows to find a number of springs for application in the valves depending on a plunger stroke, coil parameters, and value of operating environment pressure.

The considered above dynamic equations of electromagnetic valves with spring at the joint of the plunger and the plug allow to determine the time of all phases in operation of the electromagnetic valves with an accumulative spring. The main interest for further research is formulation of electromagnet energy equation for each phase of operation. In addition, further research suggests determination of correlation between electrical parameters and geometrical valve dimensions.

The obtained experimental data are shown in Table II, they allow to evaluate results of electromagnetic valves comparison: the classical valves and the valves with an accumulative spring.

| Operating environment pressure, Pa | Electromagnetic valve with an accumulative spring I | Classical II | Classical III |
|-----------------------------------|-----------------------------------------------|---------------|----------------|
| $2 \cdot 10^5$                    | 0.4 / 0.16                                    | 0.65 / 0.36   | 0.3 / 0.56     |
| $3 \cdot 10^5$                    | 0.4 / 0.32                                    | 0.85 / 8.00   | 0.37 / –       |
| $4 \cdot 10^5$                    | 0.4 / –                                       | 0.95 / –      | 0.45 / –       |
| $5 \cdot 10^5$                    | 0.4 / 0.72                                    | 1.0 / 15.6    | 0.47 / –       |
| $6 \cdot 10^5$                    | 0.4 / 0.76                                    | 1.14 / –      | 0.5 / 1.12     |
| $7 \cdot 10^5$                    | 0.4 / 0.76                                    | 1.58 / 14.88  | 0.55 / –       |
| $8 \cdot 10^5$                    | 0.4 / –                                       | 1.60 / –      | 0.60 / –       |
| $1 \cdot 10^6$                    | 0.4 / 0.8                                     | Not opened    | 0.65 / 1.44    |
6. Conclusions
The performed analysis of known direct acting valves with spring element shows that, up to the present moment, the theory of optimal design of such electromagnetic valves has not yet been developed. In addition to that, there is no engineering techniques of calculation of them. According to the results, it is clear that obtained value of current for the valve I indicates that this current value is required to overcome elastic spring force of an accumulative spring. Therefore, it is reasonable to conclude that the power consumption can be reduced by using an accumulative spring. For further investigation the evaluation should be performed for a physical model that will take into consideration various designs of valves. After that, the numerical modeling should be used for comparison of obtained results of physical modeling. The next step of experimental investigation is close examination of search for basic parameters, and also, is obtaining initial information for the designing of testing devices. Later, it is expected to carry out a numerical experiment. In view of the aforementioned, new problem statement can be formulated – the development of calculation methods and theory of optimal design of electromagnetic valves with an accumulative spring.

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