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ANALYSIS OF FORCES ACTING ON THE ANCHOR-VALVE OF A PNEUMATIC SOLENOID VALVE

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Abstract. The article presents an analysis of the forces acting on the armature-valve of a pneumatic solenoid valve, which is a key element in pneumatic actuator control systems. The present study is an experimental and theoretical investigation into the influence of magnetic, pneumatic and inertial forces on the dynamics of armature movement. The findings of the analysis can be utilised to enhance the precision and efficacy of pulse collectors within intricate technical systems.

The experimental study investigated the impact of variations in the distance between the armature and the magnetic circuit, in conjunction with changes in vacuum pressure, on the electromagnetic effort necessary to actuate the valve. The findings suggest that as the air gap and vacuum pressure increase, a significantly higher magnetomotive force is required to initiate valve movement. This finding indicates a non-linear relationship between the system's pneumatic conditions and the electromagnetic force necessary for actuation.

Keywords: pulse collector, anchor valve, pneumatic solenoid, dynamics, magnetic forces, pneumatic forces, automation.

Introduction

Pneumo-electromagnetic systems, particularly high-speed solenoid valves, are widely used in automated control systems, mechatronics, and precision pneumatic actuators due to their high responsiveness and reliability. At the core of these systems is the armature-valve mechanism, whose performance is influenced by the interplay of electromagnetic, pneumatic, elastic, and inertial forces. A deep understanding of these forces is essential to improve valve dynamics, reduce actuation delays, and enhance energy efficiency.

Recent studies have shown considerable progress in optimizing solenoid valve designs to enhance dynamic performance. Wang, Zhang, and Li [1, 2, 13] proposed an optimized armature structure for annular multipole solenoid valves, demonstrating improved magnetic flux density distribution and reduced response time. Similarly, Wang and Zhang [3] analyzed the electromagnetic performance of high-speed solenoid valves, focusing on the impact of core materials and coil configuration. Their findings emphasized the importance of reducing eddy current losses, particularly when using composite iron cores [5, 14].

Morgan Stanley's 2025 report on the global robot market::
"Robotization will be faster than the introduction of driverless cars, thanks to controlled conditions of use. Morgan Stanley sees humanoid robots as a transformative force capable of changing the labor market and the global economy by 2050. However, success depends on overcoming current barriers and competition between East and West"

Dynamic simulation plays a crucial role in predicting the real-time behavior of valve components. Wislati and Haase [6] employed COMSOL Multiphysics to simulate both static and dynamic responses of electromagnetic valve actuators, highlighting the role of coupled magnetic and mechanical domains. Zhang and Wang [7] expanded on this approach through multiphysics modeling of electromagnetic flow valves, offering insights into structural optimization and temperature effects.

The inertial effects and pressure differential forces are significant contributors to system behavior. [8] developed a comprehensive model of direct-acting solenoid valves, evaluating the influence of spring stiffness and armature mass. Moreover, [9, 10, 15] examined the interaction of key parameters such as coil current, armature mass, and air pressure, revealing their combined impact on electromagnetic force generation and valve stability.

Despite these advancements, a gap remains in the holistic analysis of all acting forces within the armature-valve assembly during high-frequency switching. The present study aims to fill this gap by offering a comprehensive evaluation of electromagnetic, pneumatic, elastic, and inertial forces in a pulse-operated solenoid valve system. The results are intended to inform the design of next-generation pneumo-electromagnetic actuators with optimized dynamic characteristics.

Problem Statement

The performance and reliability of a pneumo-electromagnetic valve are critically dependent on the dynamic interaction of forces acting on its central moving element — the armature-valve. These forces include the following:

- the electromagnetic force F_{el}, generated by the coil when current flows through it,
- the pneumatic force caused by the pressure difference $P_A - P_V$ across the upper and lower chambers of the valve [17],
- and the gravitational force G_V due to the weight of the armature.

A schematic representation of the valve's geometry and the acting forces is shown in Figures 1 and 2.

> *Warren G. Bennis, Professor at the University of Southern California*
> ***"The factory of the future will have only two employees: a man and a dog. The man will be there to feed the dog. The dog will be there to keep the man from touching the equipment."***
> *(A humorous but telling quote about the role of automation)*

The challenge arises during the stroke transition, particularly when the armature must overcome pneumatic resistance and its own weight to initiate upward motion. This occurs during the changing phases.

Despite the availability of electromagnetic or pneumatic models in current literature [2, 8, 10, 16] few studies consider their combined effect on switching dynamics in real working conditions. In most cases, simplifying assumptions such as constant air gap or negligible pressure resistance are used, which do not reflect actual valve behavior.

Therefore, this study addresses the need for a dynamic model that accurately accounts for:

- the relationship between electromagnetic force and air gap geometry,
- pressure differentials acting on the armature during operation,
- and gravitational load, which becomes relevant in vertical configurations.

Such a model will contribute to the design of more efficient solenoid valve systems and provide a deeper understanding of the actuation process in high-speed, pressure-sensitive applications.

Mathematical model of the magnetomotive force of an electromagnet in ensuring the functioning of the 'Suction' and 'Compression' strokes

Consider the system of forces acting on the anchor valve in the following operating modes. Consider the schemes of operation.

Suction stroke. The anchor-valve is raised and is subjected to the forces (**Fig. 1**).

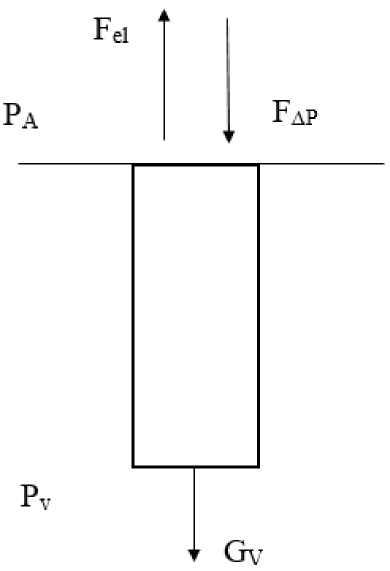

Fig. 1. Scheme of the action of forces on the anchor-valve in the ‘suction’ stroke:
P_A – air pressure, kPa; P_V - vacuum pressure, kPa, F_{el} – electromagnetic force, H , G_V – the weight of the armature-valve, kg, $F_{\Delta P}$ - the force caused by the pressure difference, H.

To keep the armature-valve in the ‘sucking’ mode, write down the equilibrium equation:

$$F_{el} = F_{\Delta P} + G_V \tag{1}$$

The electromagnetic force component is determined by formula [11]:

$$F_{el} = \frac{(IW)^2 \cdot S_{MP} \cdot \mu_0}{2 \cdot \delta^2}, \tag{2}$$

where IW– magnetomotive force of the electromagnet, A·turn; S_{MP} - cross-sectional area of the magnetic circuit of the electromagnet, m^2; μ_0 – magnetic permeability in vacuum, $\mu_0 = 4 \cdot \pi \cdot 10^{-7}\ \mathrm{Gn}/\mathrm{m}$; δ – gap between the armature-valve and the end of the magnetic circuit, m.

The strength of the pressure difference is determined by the formula:

$$F_{\Delta P} = (P_A - P_V) \cdot \sum S_{AT} \tag{3}$$

where S_{AT} - total cross-sectional area of the holes in the electromagnet body, (see Fig. 2.):

$$\sum S_{AT} = \frac{\pi \cdot d_{apr}^2}{4} \cdot n_{apr} \tag{4}$$

where n_{apr} – is the number of apertures connected to the atmosphere, $n_{apr} = 10\ units$

The gravitational force of the valve weight is accordingly:

$$G_V = m_V \cdot g, \tag{5}$$

where m_V – weight of the valve armature, kg

Then expression (1) will take the form:

$$\frac{(IW)^2 \cdot S_{MC} \cdot \mu_0}{2 \cdot \delta^2} = (P_A - P_V) \cdot \sum S_{AT} + m_V \cdot g\,. \tag{6}$$

The cross-sectional area of the magnetic circuit of the electromagnet is calculated by the expression:

$$S_{MC} = \pi \cdot (R_1^2 - R_2^2 + R_3^2)\,. \tag{7}$$

From formula (6), we determine the magnetomotive force of the electromagnet depending on the technological characteristics and structural parameters of the pulse collector.:

$$IW = \sqrt{\frac{(P_{AT} - P_V) \cdot d_{apr}^2 \cdot n_{apr} \cdot \delta^2}{2 \cdot \mu_0 \cdot (R_1^2 - R_2^2 + R_3^2)} + \frac{m_V \cdot 2 \cdot \delta^2 \cdot g}{\mu_0 \cdot \pi \cdot (R_1^2 - R_2^2 + R_3^2)}}. \tag{8}$$

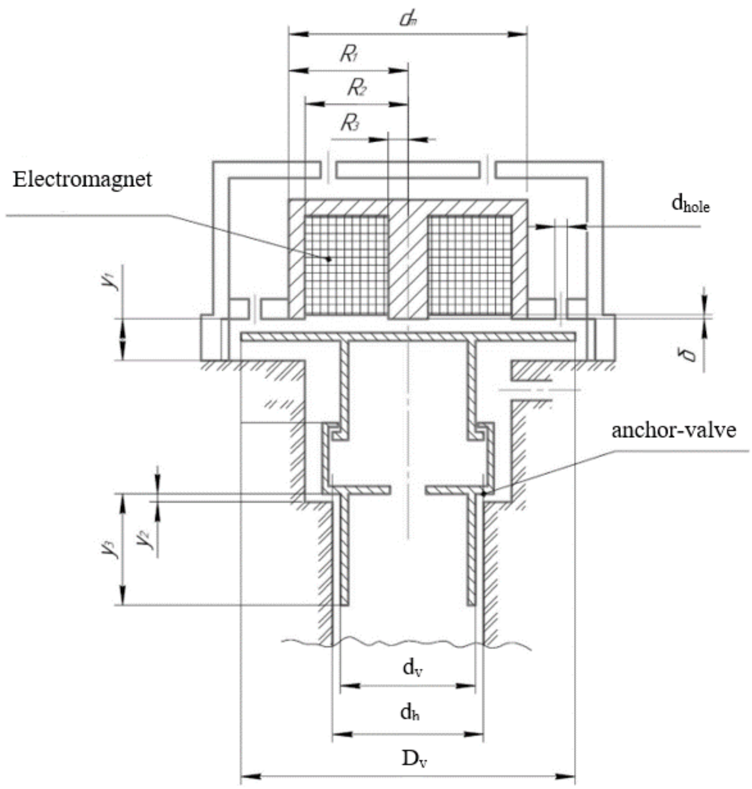

Fig. 2. Diagram of the 'anchor-valve-solenoid' system

Let us simulate the condition of holding the armature-valve in the upper position, ensuring the functioning of the 'sucking' stroke by the pneumatic electromagnetic pulse collector (Fig. 3, Fig. 4).

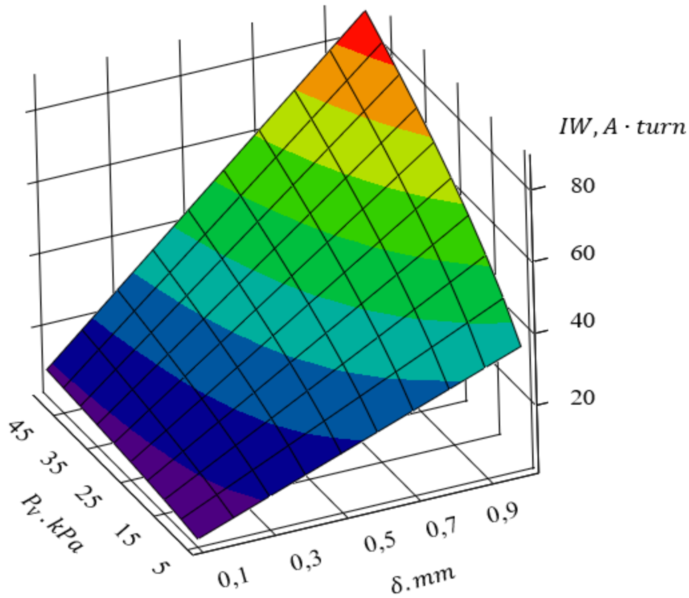

Fig. 3. Dependence of the magnetomotive force of the electromagnet (IW) for holding the armature-valve in the sucking stroke on the vacuum pressure (P_V) and the distance (δ) between the surface of the armature-valve and the magnetic circuit of the electromagnet

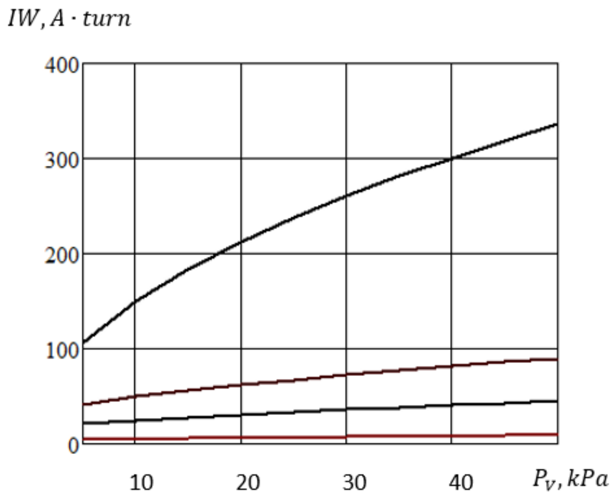

Fig. 4. Dependence of the magnetomotive force of the electromagnet (IW) for the condition of the armature-valve opening at the vacuum pressure (P_V) and the distance (δ) between the surface of the armature-valve and the magnetic circuit

The simulation results show that with an increase in the gap between the upper plane of the armature-valve and the magnetic circuit and with an increase in vacuum pressure, the value of the magnetomotive force of the electromagnet increases. For example, with a gap of $\delta = 0{,}1\ mm$, the number of ampere turns of the electromagnet to hold the armature-valve in the 'sucking' stroke exceeds $IW = 9\ A \cdot turn$ and a vacuum pressure of $P_V = 50\ kPa$. If the gap is $\delta = 1\ mm$ and the vacuum pressure is $50\ kPa$, the solenoid must have $IW = 90\ A \cdot turn$ to hold the armature valve in the up position. As the gap δ increases, the magnetomotive force of the electromagnet should increase.

In the 'compression' mode, the armature-valve will be in the lower position. The gap between the armature-valve and the magnetic circuit will be y_1.

Then the electromagnetic force will be determined by the relationship:

$$F_{el} = \frac{(IW)^2 \cdot S_{MC} \cdot \mu_0}{2 \cdot (\delta + y_1)^2}. \tag{9}$$

The strength of the pressure difference is determined by the following relationship:

$$F_{\Delta P} = (P_A - P_V) \cdot \left(R_{h1}^2 - R_V^2\right), \tag{10}$$

where R_h – hull radius, m; R_V – radius of the armature - valve, m.

Then the dependence (8) for the condition of the armature-valve 'opening' in the 'compression' stroke will be as follows:

$$IW = \sqrt{\frac{(P_A - P_B) \cdot (R_{K1}^2 - R_{Я}^2) \cdot (\delta + y_1)^2 \cdot 2}{\mu_0 \cdot (R_1^2 - R_2^2 + R_3^2)} + \frac{m_Я \cdot (\delta + y_1)^2 \cdot 2}{\mu_0 \cdot \pi \cdot (R_1^2 - R_2^2 + R_3^2)}}. \tag{11}$$

In the 'compression' mode, the armature-valve will be in the lower position. The gap between the top plane of the armature-valve and the end of the solenoid magnetic circuit will be a maximum of $\delta = 4\ mm$.

With a gap $\delta + y_1 = 0{,}004\ m$ to 'opening' the armature-valve from the lower position (transition from the "compression" to the 'sucking' stroke) and change the vacuum pressure from $P_V = 5\ kPa$ to $P_V = 50\ kPa$, the magnetomotive force of the electromagnet must be provided from $IW = 106\ A \cdot turn\ to\ IW = 335\ A \cdot turn$.

Results of experimental studies of the magnetomotive force of an electromagnet

The results of the study of the magnetomotive force of an electromagnet are shown in **Fig. 5** in the form of graphs. The obtained values of the magnetomotive force allow us to rationally select an electromagnet to bridge gaps and counteract vacuum pressure. The study was carried out for vacuum pressures (P_V) of 50 kPa, 25 kPa, 5 kPa, and for a gap (δ) between the electromagnet and the anchor-valve of 0.1, 0.5, and 0.9 mm.

The research results show that with an increase in the gap δ between the anchor-valve and the electromagnet from 0,1 to 0,9 mm and an increase in the vacuum pressure P_V inside the body of the pneumatic electromagnetic pulse collector from 5 kPa to 45 kPa, the magnetomotive force increases. At a maximum pressure P_V of 45 kPa and a maximum gap δ of 0,9 mm, the magnetomotive force required to overcome this gap by the armature-valve is $IW = 120\ A \cdot turn$.

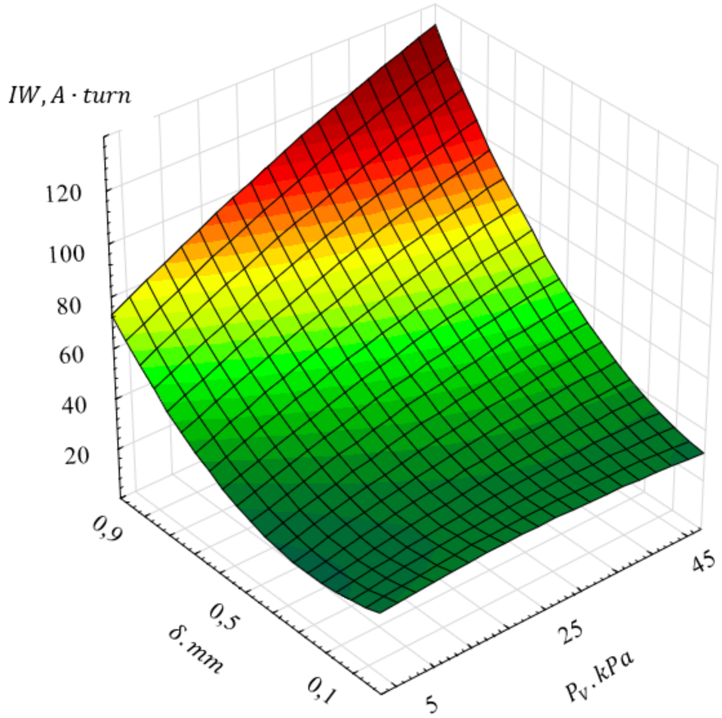

Fig. 5. Dependence of the magnetomotive (IW) force on the vacuum pressure (P_V) in the collector and the gap (δ) between the electromagnet and the anchor valve

Therefore, it can be posited that as the vacuum pressure and the gap between the armature valve and the electromagnet increase, the magnetomotive force must also increase..

Conclusions

This study presents a comprehensive analysis of the forces acting on the anchor valve in a pneumatic solenoid valve used in pulse-controlled actuators. The following conclusions have been drawn through a rigorous process of theoretical modeling and experimental validation:

1. The combined action of electromagnetic, pneumatic, and gravitational forces plays a critical role in determining the switching behavior of the armature-valve. Accurate modeling of these forces is essential for ensuring reliable operation under variable load conditions.
2. The air gap (δ) and vacuum pressure (P_V) are the most influential parameters affecting the required magnetomotive force (MMF). As both values increase, the MMF must be increased exponentially to maintain valve actuation.
3. The derived analytical model effectively predicts the MMF required for different operating phases — suction and compression — and incorporates key geometric and physical parameters of the system. The model's predictions are in close agreement with the experimental results.

4. Experimental results confirm that to initiate valve opening from the lower position, the MMF (IW) must range from 106 A·turn to 335 A·turn, depending on the vacuum pressure (P_V) (5–50 kPa) and the gap $\delta + y_1 = 0{,}004\ m$.

5. The proposed model can be used as a design tool for optimizing solenoid valve dimensions and coil configurations in pressure-sensitive applications.

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