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Oscillatory Step Rotary Pneumatic Drives in Gas Transmission Systems

Osinskiy Yuriy, Danilov Vadim*

Sevastopol National Technical University, Sevastopol, Ukraine 99011

Abstract

The article targets to solve the task to enable automated control of the proportional supply of natural gas. This requires to develop the system of automated control for the movement of the output element of the oscillatory step rotary pneumatic drive based on its mathematical model.

Keywords: driving and driven elements; pneumatic drives; gas transmission systems

1. Introduction

The area of application of pneumatic drives is very broad: industrial robots, functional devices of technological systems, transportation systems, and any devices, which perform discrete movements of actuators.

A separate area of their widespread use is the processes of controlling latches of gas transmission systems. This is particularly important for the Ukrainian economy, which largely depends on the supply and domestic production of natural gas.

The main objective here is to provide automatic control for the proportional supply of natural gas, which is extremely difficult when using existing valves that regulate its flow based on the principle of "open-closed". Application of other types of drives for this purpose is impossible, since they pose an explosive and flammable hazard. The use of pneumatic drives is also simplified by the fact that its energy source is gas in the pipelines.

Automation of gas distribution stations enables remote control by the dispatcher in real time and improves

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* Corresponding author. Tel.: +38 099 051 3751; fax: +38 069 243 3572.
E-mail address: vdmd@rambler.ru

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operational safety of pipelines and accuracy of parameters' control. Gas shocks and wave processes in gas pipelines are excluded.

In order to convert the energy of natural gas flowing through pipelines into compressed air energy sufficient to provide enough pressure to power the actuators, a "gas-air" booster pump is used. This keeps existing latches and pressure regulators used in the gas industry, while only their modernization by means of installation of the appropriate drives is carried out.

The goal of this research is to develop the algorithm of program control that ensures the turn of the leading element from the initial to the final position where it is stopped.

Research methods include the use of the apparatus of mathematical analysis, analytical mechanics, thermodynamics, the control theory and mathematical statistics.

Literature analysis shows that the most important task of automation and control of production equipment in industrial plants is to develop drives for actuators of technological equipment that was reflected in the works of the following authors M.A. Mamontov, E. Hertz, G. Kreinina, V.N. Dmitrieva, A.G. Holzunova, V.I. Pogorelov, B.N. Lokotosh, V.Y. Kopp, E.V. Pashkov and other authors [2,3,4,18,14,8,24,17,12,13,21].

Research aimed at development of oscillating step rotary pneumatic drives (OSRPD), which were first used to control latches in gas transmission systems, will expand the functionality of the pneumatic actuators and thus enhance the competitiveness of the equipment in the various fields of engineering at the Ukrainian and world markets.

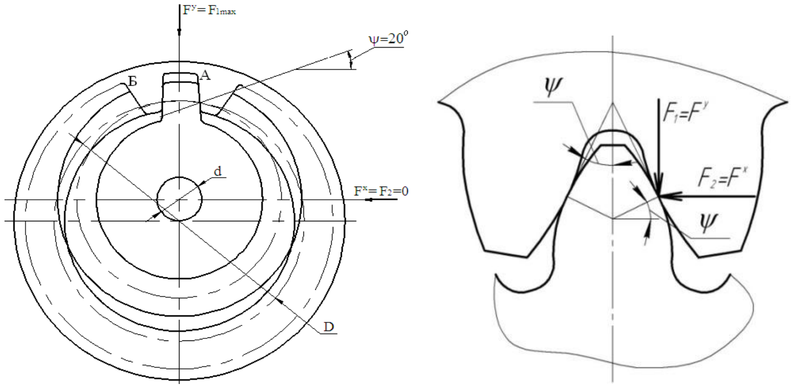
Operational dynamics of OSRPD is complex and its design should not be based on the intuitive considerations of even a highly qualified developer. It should be based on mathematical models and the results of calculations obtained by using them.

It should be noted that the efficiency of OSRPD depends on a well-designed control system. Since this multi-dimensional object has rather complex nonlinear dynamic characteristics, the issues of its control require additional research.

The OSRPD functioning principle is described below. It contains a driving and a driven toothed wheel. The driving wheel makes plane-parallel circular oscillations, while the driven wheel makes a rotational movement. The kinematics of this gearing is very similar to the kinematics of wave transmission.

The difference is that there is no deformation of the driving element, instead of which the mentioned above plane-parallel movement along the circumference is carried out. These circular oscillations of the driving element are caused by the forces perpendicular to the axis of rotation of the driven element. These forces are created by pneumatic elements of a certain type, hereafter referred to as pneumatic drives (PD). The stop of the driving element occurs when forces acting on it are equal to zero. The step mode is achieved by the appropriate switching of the PD by the given algorithm.

The geometry of interaction between the driving and driven elements are shown in Figure 1.



a) b)

Fig.1. Geometry of interaction between the driving and driven elements of OSRPD:

a – location of the driving and driven elements when $F^y = F_{1max}$; $F^x = 0$;

b – schematic chart of the forces application at the point of contact

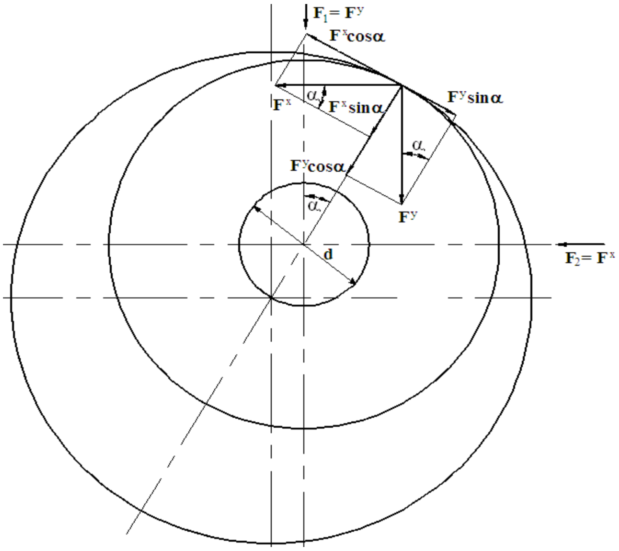


Fig. 2. Schematic chart of the forces' action at the point of contact between driving and driven elements.

When making a full circle of oscillations of the driving element, the driven element turns by the angle:

$$\gamma^{ок} = \frac{z_1 - z_2}{z_1} 2\pi \quad , \tag{1}$$

where $d = D_1 - D_2 = (z_1 - z_2)m_z$; $x_1^{ок} = \pi d = \pi(z_1 - z_2)m_z$; $S(\alpha) = \alpha r$, $r = \sqrt{x^2 + y^2}$.

$$i = \frac{\gamma^{ок}}{x_1^{ок}} = \frac{2}{D_2} \quad \gamma = i \cdot x_1 = \frac{2}{D_2} \cdot x_1 ; \quad \dot{\gamma} = \frac{2}{D_2} \cdot \dot{x}_1 .$$

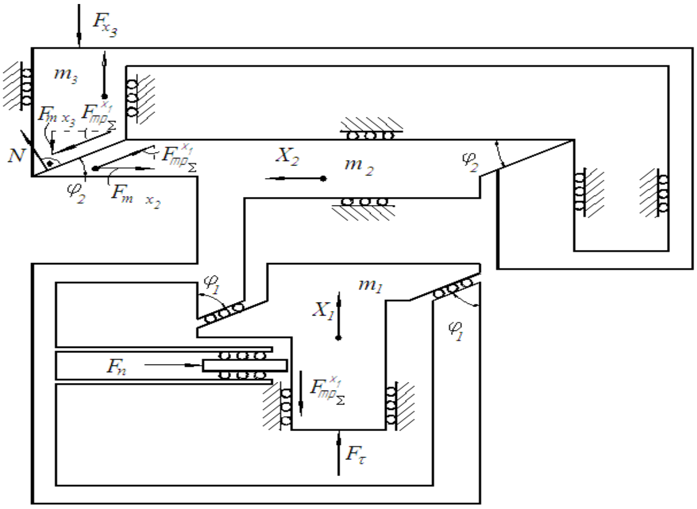


Fig. 3. The kinematic model of the oscillating step pneumatic drive of rotary action.

$$tg\phi_1 = \frac{D_2}{d};\quad tg\phi_2 = \frac{d}{D_2}.$$

$$tg\phi_3 = tg\phi_1 tg\phi_2 = 1.$$

Consequently,

$$x_2 = x_1 tg\phi_1 = x_1 \frac{D_2}{d};$$

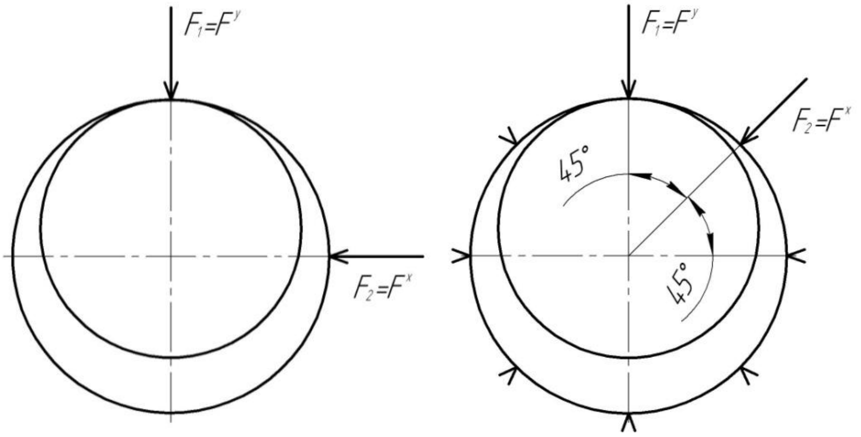
$$x_3 = x_1 tg\phi_3 = x_1,$$

Tangential F_τ and normal F_n components of forces are equal to:

$$F_\tau = F^x \cos\alpha - F^y \sin\alpha; \tag{2}$$

$$F_n = F^x \sin\alpha + F^y \cos\alpha. \tag{3}$$

Options of control for OSRPD



a) b)

Fig. 4. Layouts of the membrane pneumatic drives:
a) four; b) eight.

2. Controlling OSRPD that contains four membrane pneumatic drives (MPD) placed at 90^0 angle relative to each other. (Fig. 4,a)

2.1. Controlling OSRPD when the displacement is from 0^0 to 90^0

The initial conditions: $F_1 = F^y = F_{1max}$; $F_2 = F^x = 0$.

The final conditions: $F_1 = F^y = 0$; $F_2 = F^x = F_{2max}$.

2.2. Controlling OSRPD when the displacement is from 0^0 to 45^0

The initial conditions: $F_1 = F^y = F_{1max}$; $F_2 = F^x = 0$.

The final conditions: $F_1 = F^y = F_{1max}$; $F_2 = F^x = F_{2max}$.

2.3. Controlling OSRPD when the displacement is from 45^0 to 90^0

The initial conditions: $F_1 = F^y = F_{1max}$; $F_2 = F^x = F_{2max}$.

The final conditions: $F_1 = F^y = 0$; $F_2 = F^x = F_{2max}$.

3. Controlling OSRPD that contains eight membrane pneumatic drives (DPD) placed at 45^0 angle relative to each other. (Fig. 4,b)

3.1. Controlling OSRPD when the displacement is from 0^0 to 45^0.

The initial conditions: $F_1 = F^y = F_{1max}$; $F_2 = F^x = 0$.

The final conditions: $F_1 = F^y = 0$; $F_2 = F^x = F_{2max}$.

3.2. Controlling OSRPD when the displacement is from 0^0 to $22,5^0$

The initial conditions: $F_1 = F^y = F_{1max}$; $F_2 = F^x = 0$.

The final conditions: $F_1 = F^y = F_{1max}$; $F_2 = F^x = F_{2max}$.

3.3. Controlling OSRPD when the displacement is from $22,5^0$ to 45^0

The initial conditions: $F_1 = F^y = F_{1max}$; $F_2 = F^x = F_{2max}$.

The final conditions: $F_1 = F^y = 0$; $F_2 = F^x = F_{2max}$.

The forces F_1 and F_2 are created by membrane pneumatic drives and affect the driving element.

For cases 1.1 and 2.1, when in the initial position at $\alpha = 0$, $F_1 = F_{1max}$, $F_2 = 0$ and in the final position at $\alpha = \alpha_k$ $F_1 = 0$, $F_2 = F_{2max}$, equations describing the change in pressure values in planes are:

$$\frac{dP_2}{dt} = \frac{1}{x_{02} + x_{шm2}} \left(\frac{RT}{S_2} G_2 - P_2 \left| \dot{x}_{шm2} \right| \right); \tag{4}$$

$$\frac{dP_1}{dt}=\frac{1}{x_{01}+x_{s\,шт}+x_{шт1}}\left(\frac{RT}{S_1}G_1-P_1\left|\dot{x}_{шт1}\right|\right), \tag{5}$$

where P_1, P_2 - pressure values in working planes in the corresponding membrane drives; x_{01}, x_{02} - coordinates that determine volumes of idle pneumatic drives; $x_{s\,шт}$ - maximum stroke of pneumatic drives' rod; $x_{шт1}, x_{шт2}$ - current coordinates of pneumatic drives rods; $\dot{x}_{шт1}, \dot{x}_{шт2}$ - speeds of rods of pneumatic drives; R - the universal gas constant; T - the absolute temperature; S_1, S_2 - effective areas of membranes ; G_1, G_2 - mass flow rate of air into the cavities of the corresponding drives.

Positions and speeds of pneumatic drives' rods are determined by the position and speed of the driving element:

$$x_{шт1}=\frac{d}{2}-\frac{d}{2}\cos\alpha=\frac{d}{2}(1-\cos\alpha); \tag{6}$$

$$x_{шт2}=\frac{d}{2}\sin\alpha; \tag{7}$$

$$\dot{x}_{шт1}=\frac{d}{2}\sin\alpha; \tag{8}$$

$$\dot{x}_{шт2}=\frac{d}{2}\cos\alpha. \tag{9}$$

Mass flow rates of air G_1 and G_2 are determined from the expressions:

$$G_2=\begin{cases}\mu_2 f_2 P_M\sqrt{\dfrac{1}{2RT}}, & \dfrac{P_2}{P_M}\le 0{,}5;\\[2ex] \mu_2 f_2 P_M\sqrt{\dfrac{2}{RT}\left(1-\dfrac{P_2}{P_M}\right)\dfrac{P_2}{P_M}}, & \dfrac{P_2}{P_M}>0{,}5;\end{cases} \tag{10}$$

$$G_1=\begin{cases}\mu_1 f_1 P_1\sqrt{\dfrac{1}{2RT}}, & \dfrac{P_a}{P_1}\le 0{,}5;\\[2ex] \mu_1 f_1 P_1\sqrt{\dfrac{2}{RT}\left(1-\dfrac{P_a}{P_1}\right)\dfrac{P_a}{P_1}}, & \dfrac{P_a}{P_1}>0{,}5,\end{cases} \tag{11}$$

where f_1 and f_2 are areas of flow sections for supply and return lines; μ_1 and μ_2 - flow coefficients.

To account for the lag response of the communication equipment, this lag is represented by the inertial element of the first order. The lag's output parameters (areas f_1 and f_2) are determined from:

$$f_i=f_{i\,max}(1-e^{-\lambda_i t}),\ (i=1,2);$$

$$\lambda_i = \frac{1}{\tau_i},$$

where τ_i - time constant.

Forces F_1 and F_2 are determined form the expressions:

$$F_1 = p_1 S_1; \quad F_2 = p_2 S_2.$$

The equations above are corresponding to the cases 1.1, 2.1.

In cases 1.2, 2.2 the consumption G_2 is determined from the expression:

$$G_2 = \begin{cases} \mu_2 f_2 P_2 \sqrt{\dfrac{1}{2RT}}, \dfrac{P_M}{P_2} \le 0,5; \\ \mu_2 f_2 P_2 \sqrt{\dfrac{2}{RT}\left(1 - \dfrac{P_M}{P_2}\right)\dfrac{P_M}{P_2}}, \dfrac{P_M}{P_2} > 0,5. \end{cases} \tag{12}$$

Other expressions do not change.

In cases 1.3, 2.3 the consumption G_1 is determined by the same formula as in cases 1.1, 2.1.

The results of practical use of OSRPD confirm the importance of further work related to the design, modeling, and development of systems of automatic control of this type of drive.

In the course of this research, a number of long-term issues in the area of the stepper drive control were resolved.

The kinematic model of OSRPD was developed taking into account the interaction of its moving parts and the forces applied to them which enabled the required law of motion and positioning at the end point. This kinematic model allowed formalizing the description of OSRPD dynamics for the subsequent development of the mathematical model.

A mathematical model of the dynamics of motion in a limited range of the driving and driven elements of a stepper drive is developed. The elements contact through the element of zero mass. The model takes into account the influence of the friction forces, thermodynamic processes occurring in pneumatic drives, and the laws of change of the driving forces produced by pneumatic drives.

Implementation of the program control of rotation of the OSRPD output element by the predetermined angle is realized. The program control, first, ensures the tracking mode at the point of positioning, second, is optimal by the criteria of the minimum norm of error of actual coordinates in the comparison with the coordinates of the ideal linear system and , third, allows to decrease the oscillation amplitude at the point of positioning.

We have also solved the auxiliary problem of developing the ideal linear system of drive control optimal by the linear –quadratic criteria of quality.

The obtained results can be applied in the design of structures and systems of OSRPD control.

Personal contribution of the researchers is a mathematical model of OSRPD [10], a stand for experimental studies of the dynamic characteristics of OSRPD, processing the results of experimental studies [12, 13, 27], the development of the digital [20, 25] and the optimal [19] system of OSRPD automatic control KSHPP .

Perspectives of further research include solution of the problem of developing an optimal control of OSRPD as a linearized system providing discrete intervals of maximum approach of the state of the output element of the actuator to the state of ideal linear system of automated control.

References

[1] Besekerskiy V.A. Automatic regulation systems theory /V.A. Besekerskiy, E.P. Popov.– M.: Nauka Publishing House, 1972. - 768 p.

[2] Gerts E.V. Algorithm for obtaining computer-based solutions of equations of the dynamics of complex pneumatic systems /E.V. Gerts, G.V. Kreynin, M.A. Polyakova //Pneumatics and Hydraulics. – M.: Mashinostroyeniye Publishing House, 1969. - №4. - p. 31-35.

[3] Gerts E.V. Dynamic analysis of discrete pneumatic actuators /E.V. Gerts //Pneumatics and Hydraulics. - M.: Mashinostroyeniye Publishing House, 1973. - №1. - p. 17-33.

[4] Gerts E.V. Definition of response time of the discrete actuator operation /E.V. Gerts, B.P. Vilkov //Mechanics of machines, 1974. - №43. - p. 35-36.

[5] Gerts E.V. Calculation of pneumatic drives /E.V. Gerts, G.V. Kreynin. – M.: Mashinostroyeniye Publishing House, 1975. – 272 p.

[6] Gerts E.V. Formalizing up the equations of dynamics of complex pneumatic systems /E.V. Gerts, M.A. Polyakova //Pneumatic Actuators and Control Systems. - M.: Nauka Publishing House, 1971. - p. 26-35.

[7] Jury E. Pulsed automatic control systems /E. Jury. – M.: Phizmatgiz Publishing House, 1963. – 456 p.

[8] Dmitriyev V.N. Basics of pneumoautomatics /V.N. Dmitriyev, V.G. Gradetskiy. – M.: Mashinostroyeniye Publishing House, 1973. - 360 p.

[9] Kvakernaak H. Linear optimal control systems /H. Kvakernaak, R. Sivan. - M.: MIR Publishing House, 1977. - 650 p.

[10] Kopp V.Ya. Vibrational stepper actuators /V.Ya. Kopp, Ya.A. Osinskiy, V.V.Polivtsev //Optimization of production processes: Collection of research papers - Release 10. – Sevastopol: SevNTU Publishing House, 2007. – p.15-20.

[11] Kopp V.Ya. Modular pneumatic manipulators in assembly-line production /V.Ya. Kopp //Engineering production. Ser. Manufacturing automation, flexible manufacturing systems, robotics. – M.: Vniituemr, 1989. - Release 1 - p. 52.

[12] Kopp V.Ya. Stand for studying the dynamics of the vibrational stepper rotary actuator operation /V.Ya. Kopp, Ya.A. Osinskiy, O.V. Filipovich // Materials of International scientific and technical conference dedicated to the 50th anniversary of TNTU and the 165th anniversary of Ivan Pulyuy., May 19-21, 2010. Ternopil. - p.165-166.

[13] Kopp V.Ya. Experimental unit for the study of dynamic characteristics of the oscillatory stepper rotary pneumatic actuator operations /V.Ya. Kopp, Ya.A. Osinskiy, M.I.Garmatyuk //Automation: problems, ideas, solutions: Proceedings of the International Scientific and Technical Conference, September 6-10, 2010 – Sevastopol: SevNTU Publishing House, 2010. - vol.1. - p.106-109.

[14] Kreynin G.V. Regarding the choice of optimal parameters of discrete pneumatic control systems of mini machines /G.V. Kreynin //Mechanics of machines. - M.: Nauka Publishing House, 1969. - № 19-20. - p.175-182.

[15] Kreynin G.V. Pneumatic actuators of industrial robots /G.V. Kreynin //Machines and tools. - №7, 1978. - p. 24-28.

[16] Lokotosh B.N. Classification of pneumatic stepper motors /B.N. Lokotosh, V.P. Petrenko, R.A. Sinyavskiy //Methods and devices for collecting and processing measurement data. - K.: Tekhnika Publishing House, 1976. – p.15-17.

[17] Lokotosh B.N. Pneumatic stepper motors of automatic control systems /B.N. Lokotosh, V.P. Petrenko. – Kiyev: Znaniye Society of the Ukrainian SSR, 1981. – 28 p.

[18] Mamontov M.A. Variable environment body heat mechanics – basis of the theory of gas and pnuematic drives /M.A. Mamontov //Pneumatic Actuators and Control Systems. - M.: Nauka Publishing House, 1971. – p. 8-18, 80.

[19] Osinskiy Ya.A. Optimal automatic control system of pneumatic stepper vibrational actuator of rotary type /Ya.A. Osinskiy, V.Ya. Kopp, E.V. Lazareva //Automation: problems, ideas, solutions: Proceedings of the International Scientific and Technical Conference, September 5-9, 2011 – Sevastopol: SevNTU Publishing House, 2011. – p. 249-252.

[20] Osinskiy Ya.A. Digital automatic control system of vibrational stepper pneumatic drive of rotary type /Ya.A. Osinskiy, V.Ya. Kopp, E.V. Lazareva //Automation: problems, ideas, solutions: Proceedings of the International Scientific and Technical Conference, September 5-9, 2011 – Sevastopol: SevNTU Publishing House, 2011. – p. 246-249.

[21] Pashkov E.V. Industrial mechatronic systems based on pneumatic drive: Teach. manual /E.V. Pashkov, Ya.A. Osinskiy. – Sevastopol: SevNTU Publishing House, 2007. — 401 p.

[22] Pogorelov V.I. Gasdynamic calculations of pneumatic actuators /V.I. Pogorelov. - L.: Mashinostroyeniye Publishing House, 1971. - 182 p.

[23] Solodovnikov V.V. Theory of automatic control of engineering systems: Teach. manual / V.V. Solodovnikov, V.N. Plotnikov, A.V. Yakovlev. – M.: MSTU Publishing House, 1993. – 492 p.

[24] Kholzunov A.G. Basis of calculation of pneumatic actuators /A.G. Kholzunov. – M.: Mashinostroyeniye Publishing House, 1964. – 267 p.

[25] Digital automatic control system (ACS) of vibrational stepper pneumatic drive of rotary type /Ya.A. Osinskiy, V.Ya. Kopp, E.V. Lazareva and others //System technologies. Regional Interuniversity collection of scientific papers. – Release 3(74). – Dnepropetrovsk, 2011. - p. 94-102.

[26] Tsipkin Ya.Z. The theory of linear impulsive systems /Ya.Z. Tsipkin. – M.: Phizmatgiz Publishing House, 1963. – 968 p.

[27] Experimental unit for the study of dynamic characteristics of the oscillatory stepper rotary pneumatic actuator operations /Ya.A. Osinskiy, V.Ya. Kopp, O.V. Filipovich and others //«Technological systems» Journal – Lutsk. - №1(3). – 2011. – p. 98-105.