ISSN No:-2456-2165

Determination of the Magneto Hydraulic Pusher's Electromagnet Armature-Piston Attraction Time to the Core Using Mathematical Modeling

Rusudan Bitsadze
Department of Mathematics
Georgian Technical University
Tbilisi, Georgia

Simon Bitsadze
Department of Engineering Graphics and Engineering Mechanics
Georgian Technical University
Tbilisi, Georgia

Abstract:- Small lifting time of pusher's rod used as a drive gear in vehicles and machinery is one of the key factors of their reliable operation, and increasing the productivity and durability. In its turn, the push rod lifting time depends on both electromagnetic characteristics of pusher's electromagnet and on those mechanical or hydraulic resistances that are predetermined by design features of the pusher. One of the reasons of push rod lifting time increment is the resisting force of work fluid extrusion situated between the armature-piston and the electromagnet core. In order to make the magneto hydraulic pusher design even more perfect it is desirable to determine armature-piston attraction time taking hydraulic resistance into account. In the work there is established time distribution of pressure in work fluid area, is calculated the work fluid resistance when armature-piston attracts to the core and there is determined attraction time with consideration to hydraulic resistance.

Keywords:- *Magneto Hydraulic Pusher; Armature-Piston; Core; Boundary Conditions; Integration.*

I. INTRODUCTION

Different kinds of pushers find manifold use in many industry branches, where there is a necessity of electric processes transformation into mechanic ones, in particular into rectilinear translation movement [1]. Push rod movement time when lifting is the important technical characteristic of the pusher.

In magneto hydraulic pushers (MHPs) of any design a MHP electromagnet switches on right after the electric energy supply to pushers, and when electromagnet armature (in membrane MHP) or armature-piston (in membraneless MHP) completely attracts to the electromagnet core, it squeezes out the work fluid (oil) situated between them, forces it into the push rod sub-piston area and lifts push rod by working stroke value.

In case of complete attraction of armature or armature-piston they fit tightly by upper flat ring-shape butt-end surface to flat ring-shape butt end of the core and stay in this position unless electricity supply to MHP cuts off.

When two flat surfaces approach each other in the direction of their normal, a thin liquid layer located between these surfaces acts as a shock-absorber, that's why a certain time is necessary for liquid extrusion. In case of heavy thickness of a liquid layer located between these two surfaces, when these two surfaces approach each other, a resistance to their motion is sufficiently small and these two surfaces quickly approach each other, while reduction of liquid layer thickness causes increase in the liquid extrusion resistance force and the approach velocity of these two surfaces reduces.

In case of membrane magneto hydraulic pusher elaborated by us [2], when the armature of pusher's electromagnet attracts to the core, causing the extrusion of a working fluid located between ring-shaped faces of armature and core, if the liquid layer thickness is small, a liquid pressure on the ring surface circles of maximum and minimum radius is equal to the magnitude of work chamber pressure. In all other MHPs elaborated by us [3-7], when armature-piston attracts to the core a liquid is extruded through holes of their ring-shape faces. That's why, in case of liquid extrusion the fluid pressure at the minimum-radius circles of the ring-shape faces equals to the pressure value in the work chamber, i.e. to the minimum pressure in the liquid to be extruded. In its turn, a liquid pressure at the maximum-radius circle of the ring-shape face equal to the maximum pressure in the liquid to be extruded.

We set a goal to determine the movement time of armature-piston during attraction, taking into account liquid extrusion resistance force.

II. MAIN RESULTS

When armature-piston attracts to the core, the pressure P in the liquid located between them can be described by the equation [8]

$$\frac{\partial^2 P}{\partial x^2}+\frac{\partial^2 P}{\partial y^2}=\frac{12\mu}{h^3}\cdot\frac{dh}{dt}, \qquad (1)$$

where μ – is an process fluid viscosity; h – armature stroke value; t – movement time during armature attraction.

The following boundary conditions will take place

$$P\big|_{\rho=r} = P_1, \qquad (2)$$

$$P\big|_{\rho=R} = P_2, \qquad (3)$$

where the following notation is used
$P_1 = P_{\min}$,
$P_2 = P_{\max}$,

ρ is a polar radius, r and R are the small and big radiuses of the ring. If we use polar coordinates:

$$\begin{cases} x = \rho\cos\varphi, \\ y = \rho\sin\varphi, \end{cases}$$

Equation (1) is written in the following form:

$$\frac{\partial^2 P}{\partial\rho^2} + \frac{1}{\rho}\frac{\partial P}{\partial\rho} + \frac{1}{\rho^2}\frac{\partial^2 P}{\partial\varphi^2} = \frac{12\mu}{h^3}\cdot\frac{dh}{dt}. \qquad (4)$$

In order to solve the Dirichlet boundary problem (2), (3), (4) we note that the general solution of equation is a sum of general P_0 solution of Laplace equation, i.e. corresponding homogenous equation and particular solution P^* of Reynolds non-homogenous equation. As is known the solution of Laplace equation in the collar neighborhood has to be sought in the following form:

$$P_0 = A_0 + \sum_{n=1}^{\infty}\left(\frac{\rho}{R}\right)^n (A_n\cos n\varphi + B_n\sin n\varphi)$$

$$+\sum_{n=1}^{\infty}\left(\frac{r}{\rho}\right)^n (C_n\cos n\varphi + D_n\sin n\varphi) + C_o\ln\rho. \qquad (5)$$

Using a direct verification we will make sure that we can take $\frac{12\mu}{h^3}\frac{dh}{dt}\cdot\frac{\rho^2}{4}$ in the role of P^*.

Thus, the general solution of (4) equation is sought in the following form

$$P_0 = A_0 + \sum_{n=1}^{\infty}\left(\frac{\rho}{R}\right)^n (A_n\cos n\varphi + B_n\sin n\varphi)$$

$$+\sum_{n=1}^{\infty}\left(\frac{r}{\rho}\right)^n (C_n\cos n\varphi + D_n\sin n\varphi)$$

$$+C_0\ln\rho + \frac{3\mu h'\rho^2}{h^3}. \qquad (6)$$

In order that the pressure value in the hydrosystem would satisfy boundary conditions (2), (3), the following ratios have to be observed based on (4)

$$A_0 + \sum_{n=1}^{\infty}(A_n\cos n\varphi + B_n\sin n\varphi)$$

$$+\sum_{n=1}^{\infty}\left(\frac{r}{R}\right)^n (C_n\cos n\varphi + D_n\sin n\varphi)$$

$$+C_0\ln R + \frac{3\mu h'}{h^3}R^2 = P_2.$$

A_0, C_0 coefficients are determined from the system:

$$A_0 + C_0\ln r + \frac{3\mu h'}{h^3}r^2 = \frac{1}{2\pi}\int_0^{2\pi} P_1 d\varphi = P_1, \qquad (7)$$

$$A_0 + C_0\ln R + \frac{3\mu h'}{h^3}R^2 = \frac{1}{2\pi}\int_0^{2\pi} P_2 d\varphi = P_2. \qquad (8)$$

If we subtract (7) from (8) we obtain that

$$C_0(\ln R - \ln r) + \frac{3\mu h'}{h^3}(R^2 - r^2) = P_2 - P_1,$$

from where

$$C_0 = \frac{P_2 - P_1 - \frac{3\mu h'}{h^3}(R^2 - r^2)}{\ln R - \ln r}, \qquad (9)$$

and taking (7) into account

$$A_0 = P_1 - \frac{P_2 - P_1 - \frac{3\mu h'}{h^3}(R^2 - r^2)}{\ln R - \ln r}\cdot\ln r - \frac{3\mu h'}{h^3}r^2. \qquad (10)$$

A_n, B_n, C_n and D_n coefficients are determined by the equations

$$\begin{cases} \left(\frac{r}{R}\right)^n A_n + C_n = \frac{1}{\pi}\int_0^{2\pi} P_1\cos n\varphi\, d\varphi = 0, \\ A_n + \left(\frac{r}{R}\right)^n C_n = \frac{1}{\pi}\int_0^{2\pi} P_2\cos n\varphi\, d\varphi = 0 \end{cases}$$

and

$$\begin{cases} \left(\frac{r}{R}\right)^n B_n + D_n = \frac{1}{\pi}\int_0^{2\pi} P_1\sin n\varphi\, d\varphi = 0, \\ B_n + \left(\frac{r}{R}\right)^n D_n = \frac{1}{\pi}\int_0^{2\pi} P_2\sin n\varphi\, d\varphi = 0. \end{cases}$$

From these four latter ratios we obtain that

$$A_n = B_n = C_n = D_n = 0.$$

Thus, the solution of Dirichlet problem for Reynolds equation will be of the following form

$$P = P_1 - \frac{P_2 - P_1 - \frac{3\mu h'}{h^3}\left(R^2 - r^2\right)}{\ln R - \ln r}\ln r - \frac{3\mu h'}{h^3} r^2$$
$$+ \frac{P_2 - P_1 - \frac{3\mu h'}{h^3}\left(R^2 - r^2\right)}{\ln R - \ln r}\ln \rho - \frac{3\mu h'}{h^3}\rho^2,$$

which we re-write as follows

$$P = P_1 + \frac{P_2 - P_1 - \frac{3\mu h'}{h^3}\left(R^2 - r^2\right)}{\ln R - \ln r}\left(\ln\rho - \ln r\right)$$

$$+ \frac{3\mu h'}{h^3}\left(\rho^2 - r^2\right). \qquad (11)$$

(11) shows the time distribution of pressure along the radius (from r to R) in the process fluid area to be extruded.

In the dimensionless form the (11) equation will be written as follows

$$\frac{h^3}{\mu h' r^2} P = \frac{h^3}{\mu h' r^2} P_1$$
$$+ \frac{h^3}{\mu h' r^2}\frac{\left(P_2 - P_1\right)\ln\frac{\rho}{r}}{\ln\frac{R}{r}} - \frac{3\left(\left(\frac{R}{r}\right)^2 - 1\right)\ln\frac{\rho}{r}}{\ln\frac{R}{r}}$$
$$+3\left(\left(\frac{\rho}{r}\right)^2 - 1\right).$$

The resistance F of the displaced process fluid, when the armature approaches the core, is calculated via the ring D D pressure integration

$$F = \iint_D P\, dx\, dy .$$

In polar coordinates we will have

$$F = \iint_D P\rho\, d\rho\, d\varphi .$$

If we move to multiple integrals, we obtain

$$F = \int_0^{2\pi}\int_r^R P\rho\, d\rho\, d\varphi$$

$$= 2\pi\int_r^R\left(P_1\rho + \frac{P_2 - P_1 - \frac{3\mu h'}{h^3}\left(R^2 - r^2\right)}{\ln\frac{R}{r}}\rho\ln\frac{\rho}{r}\right.$$

$$\left. + \frac{3\mu h'}{h^3}\left(\rho^3 - r^2\rho\right)\right) d\rho . \qquad (12)$$

Note that when using the partial integration formula

$$\int_r^R \rho\ln\frac{\rho}{r}\, d\rho = \int_r^R \ln\frac{\rho}{r}\, d\left(\frac{\rho^2}{2}\right)$$
$$= \ln\frac{\rho}{r}\cdot\frac{\rho^2}{2}\Big|_r^R - \int_r^R \frac{\rho^2}{2}\cdot\frac{r}{\rho}\cdot\frac{1}{r}\, d\rho$$

$$= \frac{R^2}{2}\ln\frac{R}{r} - \frac{R^2 - r^2}{4} . \qquad (13)$$

Taking (13) into account, from (12) we obtain

$$F = \pi P_1\left(R^2 - r^2\right)$$
$$+ \frac{\pi\left(P_2 - P_1\right)}{\ln R/r}\left(R^2\ln\frac{R}{r} - \frac{R^2 - r^2}{2}\right)$$
$$- \frac{3\pi\mu h'\left(R^2 - r^2\right)}{h^3\ln R/r}\left(R^2\ln\frac{R}{r} - \frac{R^2 - r^2}{2}\right)$$

$$+ \frac{3\pi\mu h'}{h^3}\cdot\frac{\left(R^2 - r^2\right)^2}{2}, \qquad (14)$$

i.e. in dimensionless form

$$\frac{h^3}{\mu h' r^4} F = \frac{\pi h^3 P_1}{\mu h' r^2}\left(\left(\frac{R}{r}\right)^2 - 1\right)$$
$$+ \frac{\pi h^3\left(P_2 - P_1\right)}{\mu h' r^2\ln R/r}\left(\left(\frac{R}{r}\right)^2\ln\frac{R}{r} - \left(\frac{1}{2}\left(\frac{R}{r}\right)^2 - 1\right)\right)$$

$$- \frac{3\pi\left(\left(R/r\right)^2 - 1\right)}{\ln R/r}$$

$$\times\left(\left(\frac{R}{r}\right)^2\ln\frac{R}{r} - \frac{1}{2}\left(\left(\frac{R}{r}\right)^2 - 1\right)\right) + \frac{3\pi}{2}\left(\left(\frac{R}{r}\right)^2 - 1\right)^2 . \qquad (15)$$

Now let us re-write (15) in the following form

$$\frac{h^3 F}{\mu h' r^4} - \frac{\pi h^3 P_1}{\mu h' r^2}\left(\left(\frac{R}{r}\right)^2 - 1\right)$$
$$- \frac{\pi h^3\left(P_2 - P_1\right)}{\mu h' r^2\ln R/r}\left(\left(\frac{R}{r}\right)^2\ln\frac{R}{r} - \left(\frac{1}{2}\left(\frac{R}{r}\right)^2 - 1\right)\right)$$

$$= \frac{3\pi}{2}\left(\left(\frac{R}{r}\right)^2 - 1\right)^2$$

$$- \frac{3\pi\left(\left(\frac{R}{r}\right)^2 - 1\right)}{\ln R/r}\left(\left(\frac{R}{r}\right)^2\ln\frac{R}{r} - \frac{1}{2}\left(\left(\frac{R}{r}\right)^2 - 1\right)\right)$$

from where

$$\frac{dt}{dh}=\left(\frac{3\pi}{2}\left(\left(\frac{R}{r}\right)^2-1\right)^2-\frac{3\pi\left((R/r)^2-1\right)}{\ln R/r}\left(\left(\frac{R}{r}\right)^2\ln\frac{R}{r}-\frac{1}{2}\left(\left(\frac{R}{r}\right)^2-1\right)\right)\right)$$

$$\times\left(\frac{F}{\mu r^4}-\frac{\pi P_1}{\mu r^2}\left(\left(\frac{R}{r}\right)^2-1\right)\right.$$

$$\left.-\frac{\pi(P_2-P_1)}{\mu r^2\ln R/r}\left(\left(\frac{R}{r}\right)^2\ln\frac{R}{r}-\frac{1}{2}\left(\left(\frac{R}{r}\right)^2-1\right)\right)\right)^{-1}\cdot\frac{1}{h^3}. \quad (16)$$

Via integration of (16) equation we obtain a ratio between time and armature stroke. If armature-piston will move from h_o to h_1, when time changes from t_o to t_1 then

$$\int_{t_o}^{t_1}dt=\int_{h_o}^{h_1}\left\{\frac{3\pi}{2}\left(\left(\frac{R}{r}\right)^2-1\right)^2-\frac{3\pi\left((R/r)^2-1\right)}{\ln R/r}\left(\left(\frac{R}{r}\right)^2\ln\frac{R}{r}-\frac{1}{2}\left(\left(\frac{R}{r}\right)^2-1\right)\right)\right\}$$

$$\times\left(\frac{F}{\mu r^4}-\frac{\pi P_1}{\mu r^2}\left(\left(\frac{R}{r}\right)^2-1\right)\right.$$

$$\left.-\frac{\pi(P_2-P_1)}{\mu r^2\ln R/r}\left(\left(\frac{R}{r}\right)^2\ln\frac{R}{r}-\frac{1}{2}\left(\left(\frac{R}{r}\right)^2-1\right)\right)\right)^{-1}\cdot\frac{1}{h^3}dh. \quad (17)$$

Note that the armature attraction force F with an adequate accuracy can be considered as a constant one for sufficient small h. Based on this fact.

$$\Delta t=t_1-t_0=\frac{1}{2}\left(\frac{1}{h_o^2}-\frac{1}{h_1^2}\right)\left\{\frac{3\pi}{2}\left(\left(\frac{R}{r}\right)^2-1\right)^2-\frac{3\pi\left((R/r)^2-1\right)}{\ln R/r}\left(\left(\frac{R}{r}\right)^2\ln\frac{R}{r}-\frac{1}{2}\left(\left(\frac{R}{r}\right)^2-1\right)\right)\right\}$$

$$\times\left(\frac{F}{\mu r^4}-\frac{\pi P_1}{\mu r^2}\left(\left(\frac{R}{r}\right)^2-1\right)\right.$$

$$\left.-\frac{\pi(P_2-P_1)}{\mu r^2\ln R/r}\left(\left(\frac{R}{r}\right)^2\ln\frac{R}{r}-\frac{1}{2}\left(\left(\frac{R}{r}\right)^2-1\right)\right)\right)^{-1}.$$

As h_0 we have to take that thickness, in case of which the resistance to movement becomes so sufficient that armature's retarded motion starts.

III. CONCLUSION

In magneto hydraulic pushers [3-7], for the case of direct current electromagnet armature-piston attraction to the core, a resistance force of working fluid extrusion located between them is established. Taking this force into account, the armature-piston movement time when pusher's electromagnet armature-piston attracts to the core is determined. This fact can be used afterwards, when projecting magneto hydraulic pushers design in order to improve their characteristics, in particular, for push rod lifting time reduction.

REFERENCES

[1]. M. P. Aleksandrov, Brakes of carrying and lifting machines. Mashinostroenie, 1976.
[2]. O. S. Ezikashvili and S. G. Bitsadze, Magneto hydraulic pusher. Authorship certificate № 582188, USSR, 1977.
[3]. S. Bitsadze and R. Bitsadze, Magneto hydraulic pusher. Patent of invention P5536, Georgian Patent, 2012.
[4]. S. Bitsadze and R. Bitsadze, Magneto hydraulic pusher. Patent of invention P5869, Georgian Patent, 2013.
[5]. S. Bitsadze and R. Bitsadze, Magneto hydraulic pusher. Patent of invention P6572, Georgian Patent, 2016.
[6]. S. Bitsadze and R. Bitsadze, Magneto hydraulic pusher. Patent of invention P6744, Georgian Patent, 2017.
[7]. S. Bitsadze and R. Bitsadze, Patent of invention P2019 6975B, Georgian Patent, 2019.
[8]. N. P. Petrov et al., Hydrodynamic theory of lubrication. State Technical and Creative Publisher, Moscow, 1934.