БЪЛГАРСКА АКАДЕМИЯ НА НАУКИТЕ . BULGARIAN ACADEMY OF SCIENCES

ПРОБЛЕМИ НА ТЕХНИЧЕСКАТА КИБЕРНЕТИКА И РОБОТИКАТА, 49
PROBLEMS OF ENGINEERING CYBERNETICS AND ROBOTICS, 49

София . 2000 . Sofia

Pneumohydraulic Amplifier with Mechanical Deviation of the Flow

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1. Interaction between a free flow and a hard plate

The interaction between flows and plates is investigated in detail at the previous stage of the present project [12]. Results have been obtained for different configurations of the plates at different values of the feeding pressure (Fig. 1).

Depending on the geometry of the plate edge, deviation or attraction of the flow can be obtained. In some configurations the deviation is at first discrete, followed by proportional, that suggests more specific ways of the use of this profile in flow devices.

In order to obtain practically usable deviations of the flow, very small movements of the plate are necessary (20 – 80 μm) and very small forces (about 0.1 N maximum). These low values allow the realization of high coefficients of amplification at second degree, fed by high pressure. The input control signal, moving the plate, can be pneumatic, hydraulic, electric, magnetostriction.

2. Amplifier principal diagram

The diagram of the amplifier, using the effect above described, is shown in Fig. 2. The input signal, in this case the pressure p_s, acts on the membrane, towards the centre of which a plate has been attached, shifted at a distance z. The flow, coming out from a nozzle with a diameter d with pressure p_2, is deviated at an angle β. The flow enters one of the two accepting nozzles of the plunger, the left, for example.

In the right side of the plunger the pressure is increased and it moves to the left, while the deviated flow stays in the middle between the two inlets.

3. Static characteristics

The relations, which give an expression for the static characteristics $Q=f(p_s)$, according to Fig. 2, are as follows:

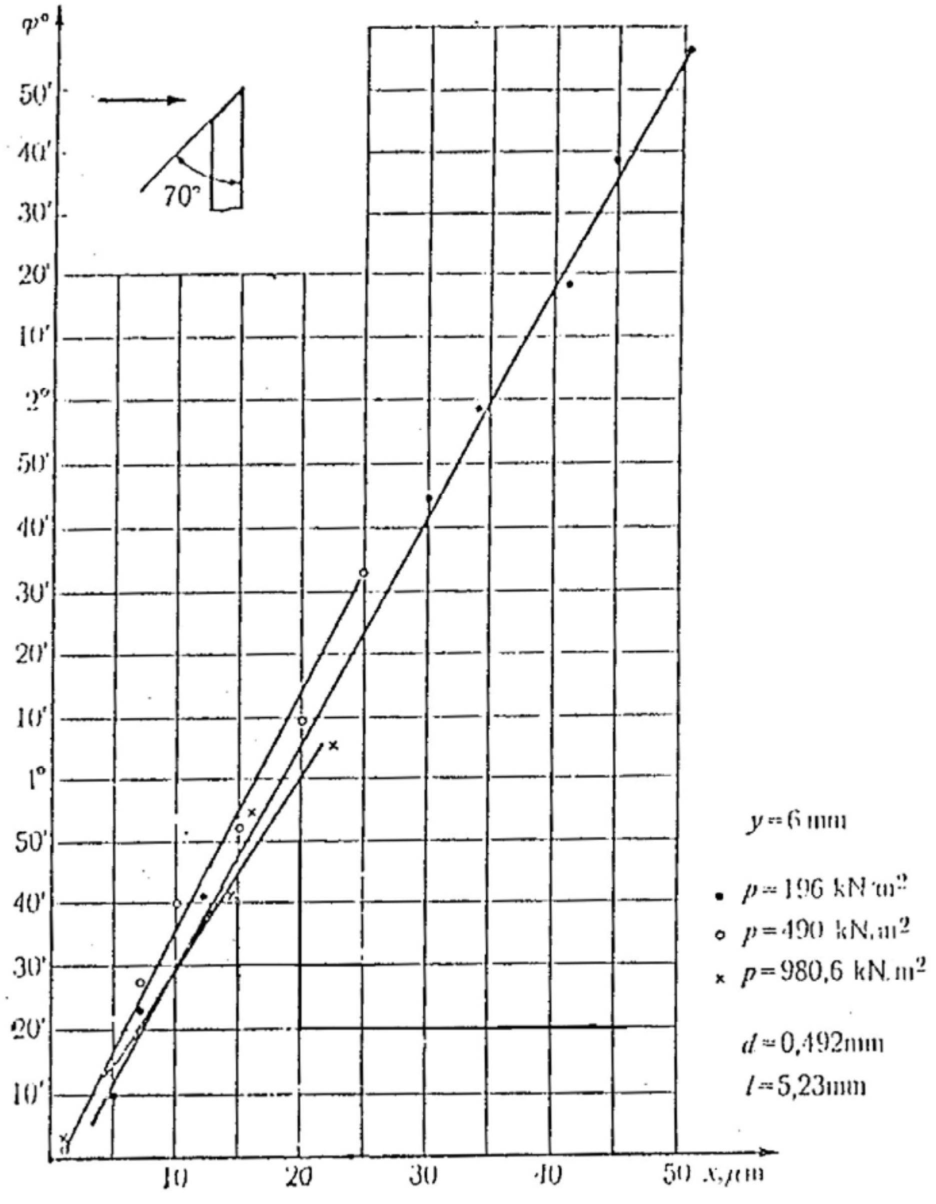
φ°
50'
40'
30'
20'
10'
2°
50'
40'
30'
20'
10'
1°
50'
40'
30'
20'
10'
70°
10
20
30
40
50 x, μm
y = 6 mm
p = 196 kN/m²
p = 490 kN/m²
p = 980,6 kN/m²
d = 0,492mm
l = 5,23mm

Fig. 1

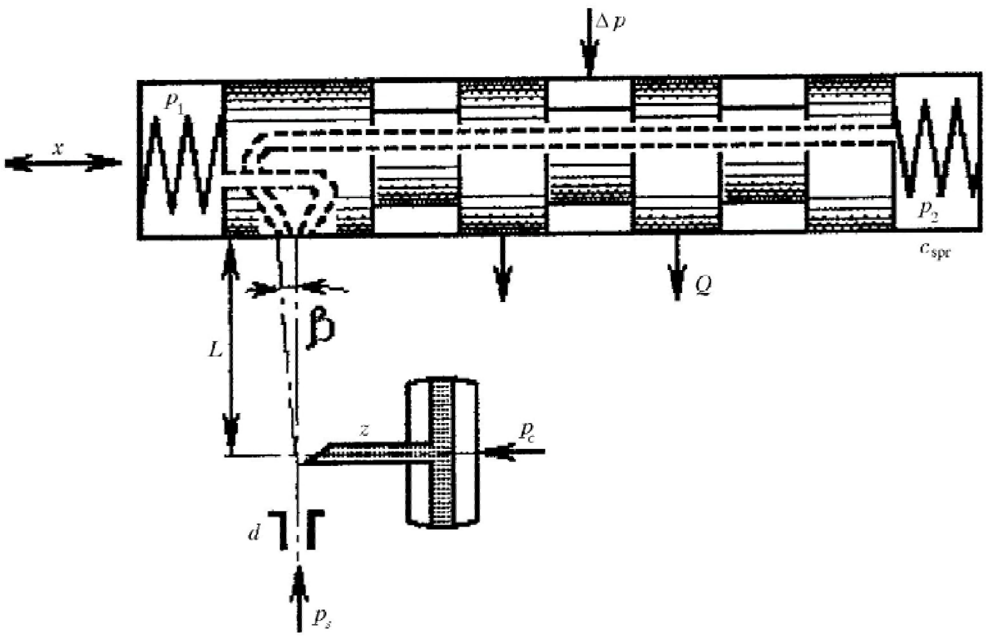
Δp
x
p_1
p_2
c_{spr}
Q
L
β
z
p_c
d
p_s

Fig. 2

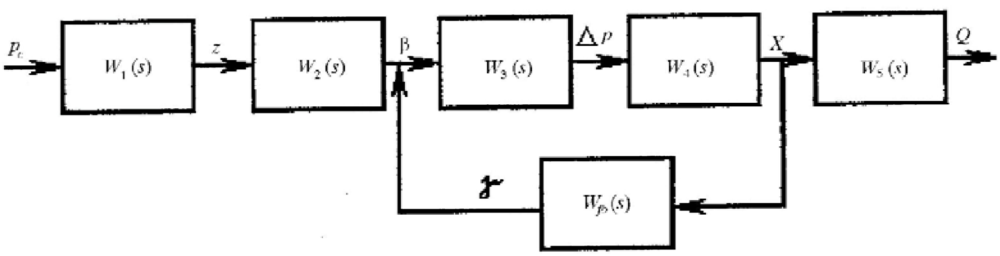
p_c
$W_1(s)$
z
$W_2(s)$
β
$W_3(s)$
Δp
$W_4(s)$
X
$W_5(s)$
Q
γ
$W_\beta(s)$

Fig. 3

(1) $$Q = f(x),$$

(2) $$x = f(p_1 - p_2),$$

(3) $$\Delta p = p_1 - p_2 = f(\beta),$$

(4) $$\beta = f(z),$$

(5) $$z = f(p_s).$$

The flow Q through the distributor depends on the speed of the fluid v and the passing pressure f_p with respect to the expression $Q = v f_p$.

At $f_p = x\, l_p$

$$v = \sqrt{\frac{2\Delta p}{\xi \rho}},$$

and for the flow it is obtained:

(6) $$Q = l_p \sqrt{\frac{2\Delta p}{\xi \rho}},$$

where f_p is the passing section in the distributor, l_p – circumference of the passing section, Δp – pressure fall in the distributor, ξ – coefficient of the local resistance.

The passing of the plunger is expressed as:

(7) $$x c_{spr} = \Delta n F_p,$$

(8) $$x = \frac{\Delta p\, F_p}{c_{spr}}.$$

The dependence between the difference of the pressure Δp on both sides of the plunger and the deviation angle of the flow is given by the expression [3]

(9) $$\Delta p = p_1 - p_2 = \frac{2p_s}{\pi r^2}\left[x_k \beta \sqrt{r^2 - (x_k \beta)^2} + r^2 \arcsin \frac{x_k \beta}{r}\right],$$

where r is the radius of the feeding nozzle; β – deviation angle of the flow, rad; $x_k = 10r$ – initial sector of the flow [1].

In entering z of the plate in the flow, the last is deviated by

(10) $$\beta = K_\beta z.$$

The coefficient K_β depends on the configuration of the plate and the value of the feeding pressure p_s and is experimentally defined (Fig. 1).

The displacement z of the plate is done transforming the input control signal (the pressure p_s) into a shift of the hard center of a thin-walled metallic membrane. It is known that the deflection of the center of a plane membrane with a hard center is

(11) $$z = A_p \frac{p_s R^4}{E h_m^3} = K_m p_s,$$

where R is the membrane radius, E – elasticity module, h_m – membrane thickness, A_p – coefficient determined by the expression

$$A_p = \frac{3}{16c^4}(1 - \mu^2)(c^4 - 1 - 4c^2 l_n c).$$

Here μ is the Poison coefficient for membrane material; $c=R/r_0$; r_0 – the radius of the membrane hard center.

The following expression for static characteristics is obtained from equations (6)–(11).

$$(12)\quad Q = \frac{2F_b l_p}{\pi r^2 c_{spr}} p_s \sqrt{\frac{2\Delta p}{\xi \rho}} \left[x_k K_\beta K_m p_s \sqrt{r^2 - (x_k K_\beta K_m p_s)^2} + r^2 \arcsin \frac{x_k K_\beta K_m p_s}{r} \right],$$

where $K_\beta = \frac{\beta}{z}$, $K_m = A_0 \frac{R^4}{E h_m^3}$.

The equation (12) leads to the limiting condition

$$r^2 - (x_k K_\beta K_m)^2 p_s \geq 0.$$

4. Dynamic characteristics

The diagram from Fig. 2 can be represented as one composed of five units and one feedback (Fig. 3).

In the first unit the input control signal, the pressure p_s is transformed into a displacement z of the plate according to equation 10. The unit is of proportional nature and its transfer function, at null initial conditions, is:

$$(13)\qquad W_1(s) = \frac{z(s)}{p_s(s)} = K_m .$$

The logarithmic amplitude frequency characteristics (LAFC) and the logarithmic frequency characteristics (LFC) are respectively:

$$(14)\qquad L_1(\varpi) = \frac{\beta(s)}{z(s)} .$$

$$(15)\qquad \psi_1(s) = 0.$$

The second unit expresses the process of deviation of the flow under an angle β as a result of the plate entering it at a distance z [13].

The unit is proportional, according to equation (10) and is frequency characteristics are as follows:

$$(16)\qquad W_2(s) = \frac{\beta(s)}{z(s)} = K_\beta ,$$

$$(17)\qquad L_2(\varpi) = 20 \lg K_\beta$$

$$(18)\qquad \psi_2(\varpi) = 0.$$

The third unit transforms the angle of flow deviation into the difference of the pressure on the two sides of the distributor plunger, $\Delta p = p_1 - p_2$.

This transformation has been expressed by equation (9).

The last one can be simplified as the first term of the right side is developed in a power series and the terms of low order are neglected. It is assumed for the second term, due to the small deviation angles ($\beta = 0 \div 6°$) that

$$\arcsin \frac{x_k \beta}{r_0} \approx \frac{x_k \beta}{r_0} .$$

Then

(19) $$\Delta p = \frac{4x_k}{\pi \rho_0} p_s \beta = K_3 \beta.$$

The frequency characteristics are as follows:

(20) $$W_3(s) = \frac{\Delta p(s)}{\beta(s)}.$$

(21) $$L_3(\varpi) = 20 \log K_3$$

(22) $$\psi(\varpi) = 0.$$

The distributor plunger is shifted at a distance x, according to equation (7), under the action of the difference in the pressure Δp.

As already known, a similar unit is of oscillating nature in the general case and respectively:

(23) $$W_4(s) = \frac{x(s)}{\Delta p(s)} = \frac{G}{T_2 s^2 + T_1 s + 1},$$

(24) $$L_4(\varpi) = 20 \lg G - 20 \lg \sqrt{(1 - \varpi^2 T^2) + \varpi^2 T_1^2},$$

(25) $$\psi_4(\varpi) = -\operatorname{arctg} \frac{\varpi T_1}{1 - T_2 \varpi^2},$$

where

$$T_1 = \frac{h}{c_{spr}};\ T_2 = \frac{m}{c_{spr}};\ G = \frac{F}{c_{spr}};$$

m is the plunger mass, c_{spr} – spring constant, F – cross section of the plunger, $h = \frac{\eta S}{\delta}$, η – dynamic viscosity, S – plunger surface, δ – distributor clearance.

The two last units are enclosed into a negative feedback (Fig. 3),

(26) $$\operatorname{tg}\gamma = \frac{x}{L}.$$

Due to the small values of the angle, it can be accepted that

$$\gamma \approx \frac{x}{L}.$$

and then

(27) $$W_{fb}(s) = \frac{\gamma(s)}{x(s)} = \frac{1}{L}.$$

The common transfer function of the two units connected by a feedback is:

(28) $$W_{3,4}(s) = \frac{W_3(s)\, W_4(s)}{1 + W_3(s) W_4(s) W_{fb}(s)}.$$

From the expression above given It is obtained that:

(29) $$W_{3,4}(s)=\frac{x(s)}{\beta(s)}=\frac{K_{3,4}}{T_{2a}s^2+T_{1a}s+1},$$

where

$$K_{3,4}=\frac{L}{1+L/K_{3G}},$$

$T_{2a}=T_2/a$, $T_{1a}=T_1/a$, $a=K_{3G}/2+1$,

and then

(30) $$L_{3,4}(\varpi)=20\ \lg K_{3,4}-20\ \lg\sqrt{(1-\varpi^2T_{2a})^2+\varpi^2T_{1a}},$$

(31) $$\psi_{3,4}(\varpi)=-\operatorname{arctg}\frac{\varpi T_{1a}}{1-\varpi^2T_{2a}}.$$

For output signal the shift x and input signal the pressure p_s, it follows:

(32) $$W_x(s)=\frac{x(s)}{p_c(s)}=W_1(s)\,W_2(s)\,W_{3,4}(s).$$

(33) $$W_x(s)=\frac{B}{T_{2a}s^2+T_{1a}s+1},$$

$$B=\frac{K_m K_\beta K_3 G}{a},$$

$$a=\frac{K_3 G}{L}+1,$$

(34) $$L_x(\varpi)=20\ \lg B-20\ \lg\sqrt{(1-\varpi^2T_{2a})^2+\varpi^2T_{1a}^2},$$

(35) $$\psi_x(\varpi)=-\operatorname{arctg}\frac{\varpi T_{1a}}{1-\varpi^2T_{2a}}.$$

The last unit connects the output flow Q and the plunger displacement (equation (6). The following expressions are valid for it:

(36) $$W_5(s)=\frac{Q(s)}{x(s)}=l_p\sqrt{\frac{2\Delta p}{\xi\rho}}=K_Q,$$

(37) $$L_5(\varpi)=20\ \lg K_Q,$$

(38) $$\psi_5(\varpi)=0.$$

The common transfer function is:

(39) $$W(s)=\frac{Q(s)}{p_c(s)}=W_1(s)\,W_2(s)\,W_{3,4}(s)=\frac{BK_Q}{T_{2a}s^2+T_{1a}s+1},$$

(40) $$L(\varpi)=L_1(\varpi)\,L_2(\varpi)\,L_{3,4}(\varpi)=20\ \lg G+20\ \lg\sqrt{(1-\varpi^2T_{2a}{}^2)+\varpi^2T_{1a}{}^2},$$

(41) $$\psi(w) = -\operatorname{arctg}\frac{\varpi T_{1a}}{1-\varpi^2 T_{2a}}.$$

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Пневмогидравлический усилитель с механическим отклонением струи

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(Р е з ю м е)

Исследована схема пропорционального пневмогидравлического усилителя, при котором входной пневматический сигнал преобразуется в перемещении пластинки с острым кромком. Последняя отклоняет масленную струю входящую в плунжер гидравлического распределителя с обратной связей по перемещении.

Выведены уравнения для статических и динамических характеристик.