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Electrohydraulic Amplifier with Mechanical Deviation of the Flow

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The interaction between incompressible fluid flow and a plate includes a whole group of phenomena, differing in the physical features of the flow deviation process. They are, for example, the longitudinal streamlining of a plate with different in their mathematical expression flows, the blow of the flow against a plate at different angles of attack, the deviation of the flow against a perpendicular plate.

There are not any detail data in references about the interaction between an axial-symmetrical flow with free limits and a mobile plate. This effect could be used for the design of fluid amplifiers with mechanical deviation of the flow. In order to investigate it, numerous experiments have to be made, resulting into some conclusions.

The present paper concerns a longitudinally streamed plate, which in its deviation from the axial position deflects the flow.

1. Interaction between a free flow and a longitudinally streamed plate

A thin plate has been placed against an immobile feed nozzle. The flow is divided into two parts, that enter the corresponding output holes (Fig. 1).

According to the references data the distribution of the relative pressure along the stream longitude is described by the expression [3]:

$$\eta = \frac{p_x}{p_s} = \frac{k}{\bar{x}^2}, \tag{1}$$

where p_x is the flow pressure; p_s – the feed pressure, $\bar{x} = x/d$ – the relative axial distance, d is the diameter of the feed nozzle.

The constant k can be represented as

$$k = \frac{k_1}{m^2}.$$

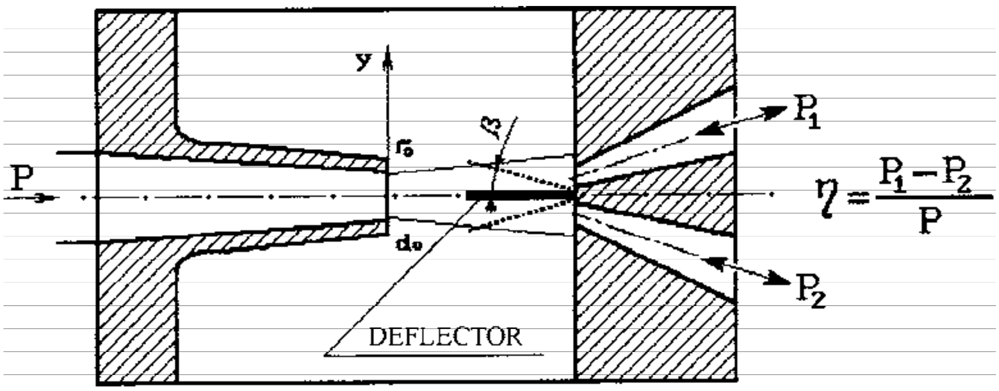


Fig. 1

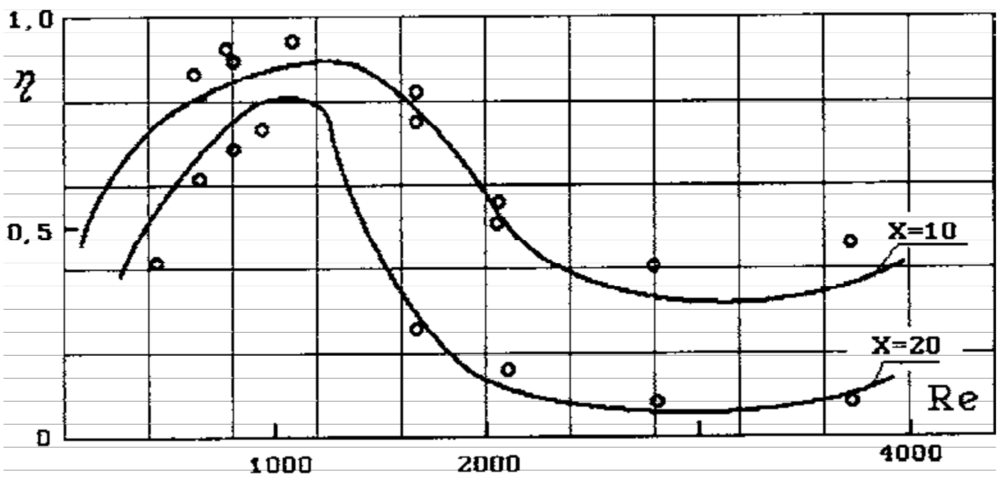


Fig. 2

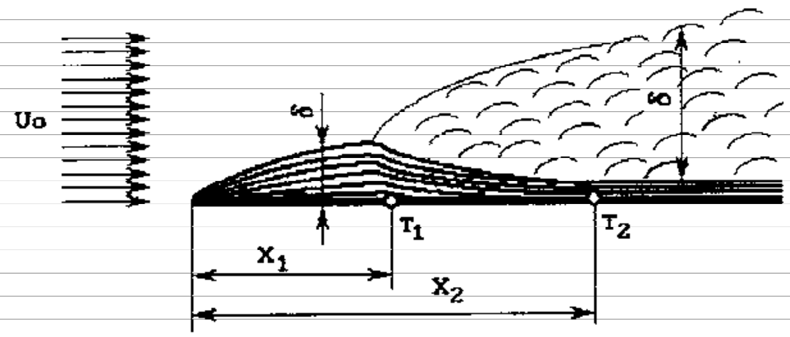


Fig. 3

For the main part of the flow m=0,2 [1].

Fig. 2 gives the experimental results for a nozzle with a diameter 1,5 mm. The characteristic $\eta = f(\mathrm{Re})$ consists of three sections: a laminar, a transition and a turbulent one [4]. The relative pressure increases in the laminar section, and taking into account the cutting tensions causing losses Δp within the range $\bar{x}$, it is according to the expression:

$$\eta = 1 - \frac{k_2 \bar{x}}{\mathrm{Re}}. \tag{2}$$

In the transition section the flow expands and the relative pressure decreases. The relation $\eta = f(\mathrm{Re})$ is described by equation (1). From the experimental data [3], the relation between the coefficients and Re can be approximated from the parabola equation:

$$m = a_0 \mathrm{Re}^2 + b_0 \mathrm{Re} + c_0, \tag{3}$$

and the relative pressure becomes:

$$\eta = \frac{k_1}{\bar{x}^2 (a_0 \mathrm{Re}^2 + b_0 \mathrm{Re} + c_0)^2}, \tag{4}$$

where a_0, b_0, c_0 are experimentally defined coefficients.

In the turbulent section, the angle of the flow expansion and the coefficient m are constant and η is computed with respect to equation (1).

The relative pressure across the flow can be defined by the expression [3]:

$$\bar{\eta} = \exp(-a \bar{y}^{\,b}), \tag{5}$$

where a and b are experimentally defined coefficients.

These coefficients are studied in [4] where their values $a \approx 3,8$ and b=2,3 have been obtained and equation 5 takes the form:

$$\bar{\eta} = \exp(-3{,}8 \bar{y}^{\,2,3}), \tag{6}$$

where $\bar{y} = y / y_{max}$.

This dependence is represented in [4] and compared with some experimental data.

The problem set is to determine the possibilities for using the effect of interaction between a free flow and an axially positioned plate for the purpose of designing a certain type of transducers.

After the basic relations of a free flow above described, we shall consider some relations in the streamlining of a thin plate, that could be used afterwards.

As shown in Fig. 3, depending on the flow mode, there exist a laminar and a turbulent boundary layer. The flow in the boundary layer is characterized by Reynold's number, expressed by the thickness δ of the boundary layer, the rate u_0 of the external flow and the kinematic viscosity v. Increasing δ, Reynold's number can achieve in a certain section its critical value Re_{cr} and after this section a turbulent boundary layer will be formed. The transition from a laminar towards a turbulent boundary layer is done at a given distance along the axis x. In the first section with length x_1, the flow is laminar. After that a transition region follows between the points T_1 and T_2 and after T_2 the turbulent flow section comes. Experimental data [6] show that the position of points T_1 and T_2 depends on the rate of the flow, the viscosity, the degree of turbulency.

The determination of the location of the point of separation T_1 is of importance for the characteristics of the flow elements, including a streamlined plate.

A simplified scheme, in which the transition section is excluded, i.e., the transition from a laminar into a turbulent flow is sudden at point T_1, is often used instead of the scheme of a boundary layer with three sections.

In [2] the following expression defining the distance x1 is given:

(7) $$\mathrm{Re}_{x1} = \frac{u_0 x_1}{v} \approx 5,10^5 \div 3,10^6;$$

(8) $$x_1 \approx (5,10^5 \div 3,10^6) v / u_0.$$

The wide range of the critical Reynold's number, defining the point of turbulences of the laminar boundary layer, is explained with the difference of the experimental conditions. The disturbances, entering the flow, for example the sharp-edge of the plate, some roughness and others, speed up the turbulization. When the plate is immobile and it is streamlined, the flow turbulency accelerates the turbulization of the laminar boundary layer.

In accordance with the characteristics of the combination "nozzle-plate" investigated and in order to create a transducer device, we shall use the minimal value of x_1:

(9) $$x_1 = 5.10^5 v / u_0.$$

The expression of Blazius in [2] is applied for the thickness of the laminar boundary layer

(10) $$\delta = 5 \sqrt{v x / u_0},$$

which will be used in the computations in our research work.

In case of a turbulent boundary layer the following expression is used in [6]:

(11) $$\delta = 0,37 \, (v / u_0)^{1/5} x^{4/5}.$$

In the combination, shown in Fig. 1, the length of the initial section $x_k = 5d$ will be probably of significance connected with the selection of the plate length.

The relation $x_1 = f(\Delta\rho)$ from equation (9) is shown in Fig. 4, and $\delta = f(x)$ – in Fig. 5 for oil with $v = 27.10^{-6}$ m²/s and $\rho = 893$ kg/m³.

The constructive parameters of the plate, serving for a deflector, are important for the flow stability and hence for the stability of the amplifier-transducer, using the combination investigated.

The experimental investigations [3], done with a deflector with thickness of 0.1 mm and 0.3 mm and length equal to the length of the initial section show, that the thickness reflects more the distribution of the pressure, when the flow is not submerged. The flow stability is considerably better at thinner plates, in this case – 0.1 mm.

In order to define the functioning characteristics, the computing of the maximal distance in the pressure on both sides of the deflector depending on the deviation angle, is of considerable significance.

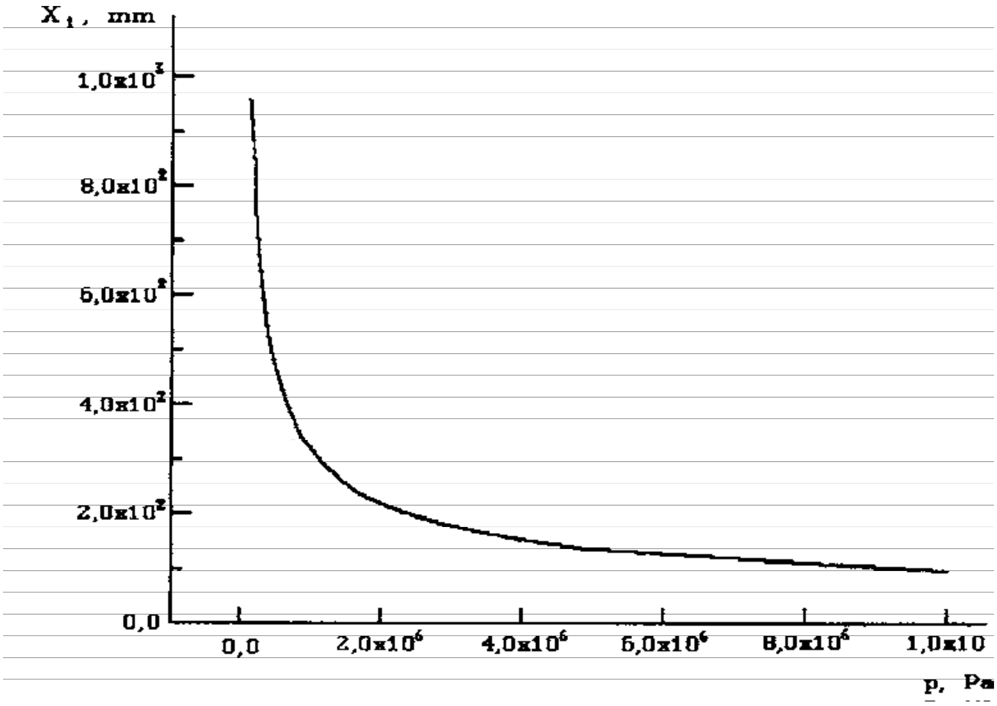
If we assume, that the pressure in the input holes after the deflector depends only on the quantity of the fluid entering them, the following dependence between the relative pressure and the deviation angle β can be derived [3]:

(12) $$\eta = \frac{2}{\pi r_0^2} \left[x_k \beta \sqrt{r_0^2 - (x_k \beta)^2} + r_0^2 \arcsin \frac{x_k \beta}{r_0} \right],$$

where r_0 is the radius of the feed nozzle; β – the deviation angle [rad]; $x_k = 5d_0$ – the initial section of the flow [1].

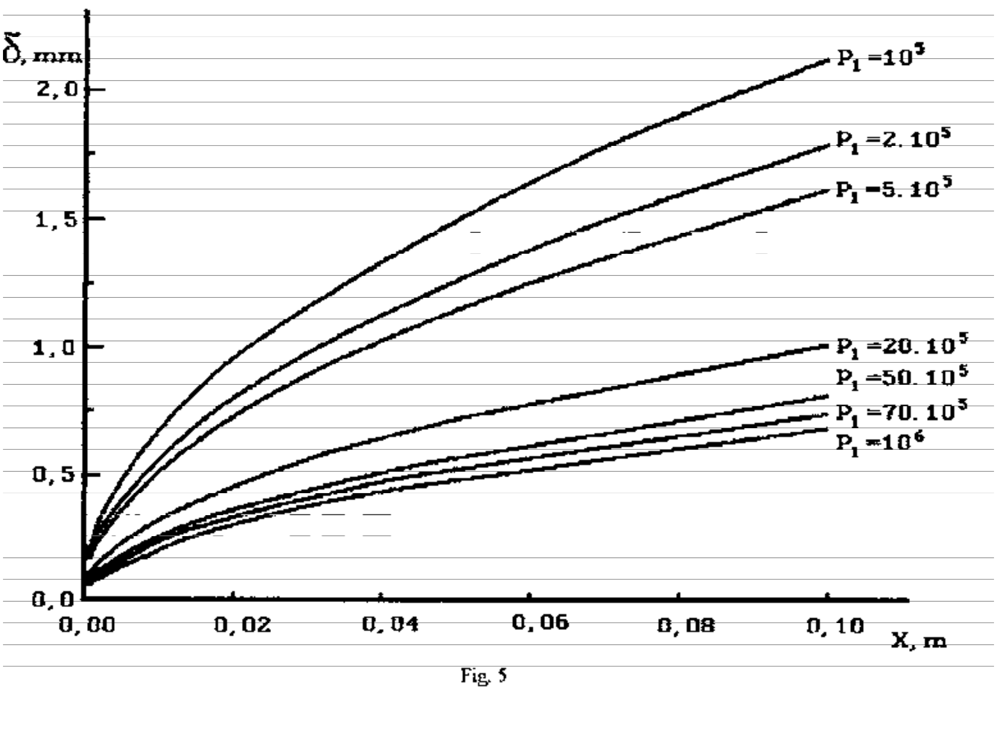
The relation $\eta = f(\beta)$ from equation (12) is shown in Fig. 6 (for $d_0 = 1,5$ mm)

In a frequency mode at $\beta = A_\beta \sin wt$ and $\eta = A_y \sin(wt + \Psi)$ from the same equation, for two cases: $A_\beta = 2° = 0,035$ rad and $A_\beta = 4° = 0,07$ rad, the variations of the relative pressure are shown in Fig. 7.



X1, mm
1,0x10³
8,0x10²
6,0x10²
4,0x10²
2,0x10²
0,0
0,0
2,0x10⁶
4,0x10⁶
6,0x10⁶
8,0x10⁶
1,0x10
p, Pa

Fig. 4



δ, mm
2,0
1,5
1,0
0,5
0,0
0,00
0,02
0,04
0,06
0,08
0,10
X, m
P1 =10⁵
P1 =2. 10⁵
P1 =5. 10⁵
P1 =20. 10⁵
P1 =50. 10⁵
P1 =70. 10⁵
P1 =10⁶

Fig. 5

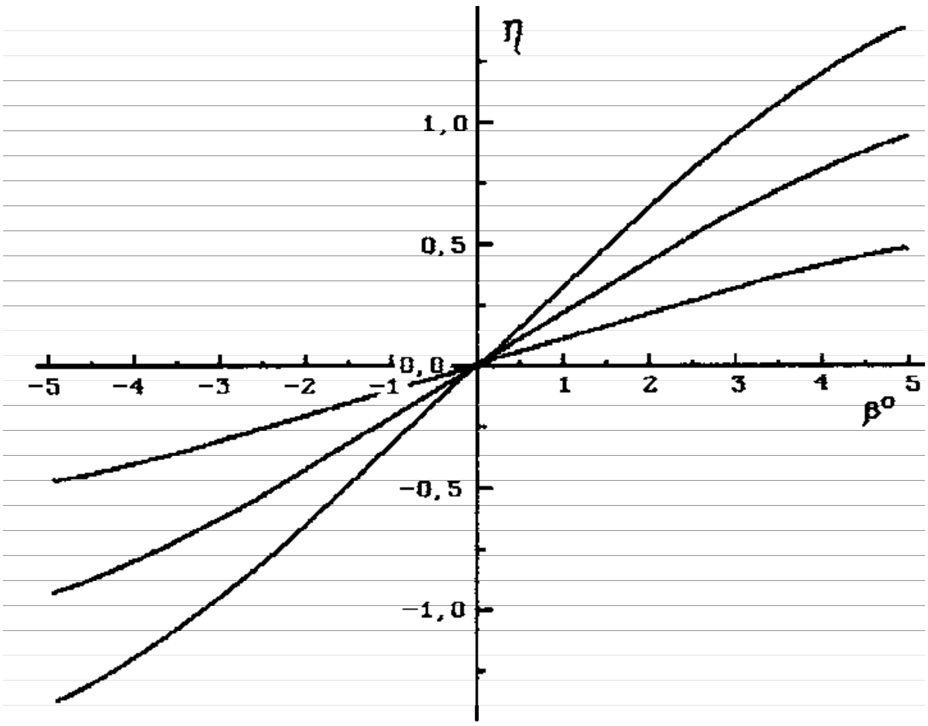

η
1,0
0,5
0,0
-0,5
-1,0
-5
-4
-3
-2
-1
1
2
3
4
5
β°

Fig. 6

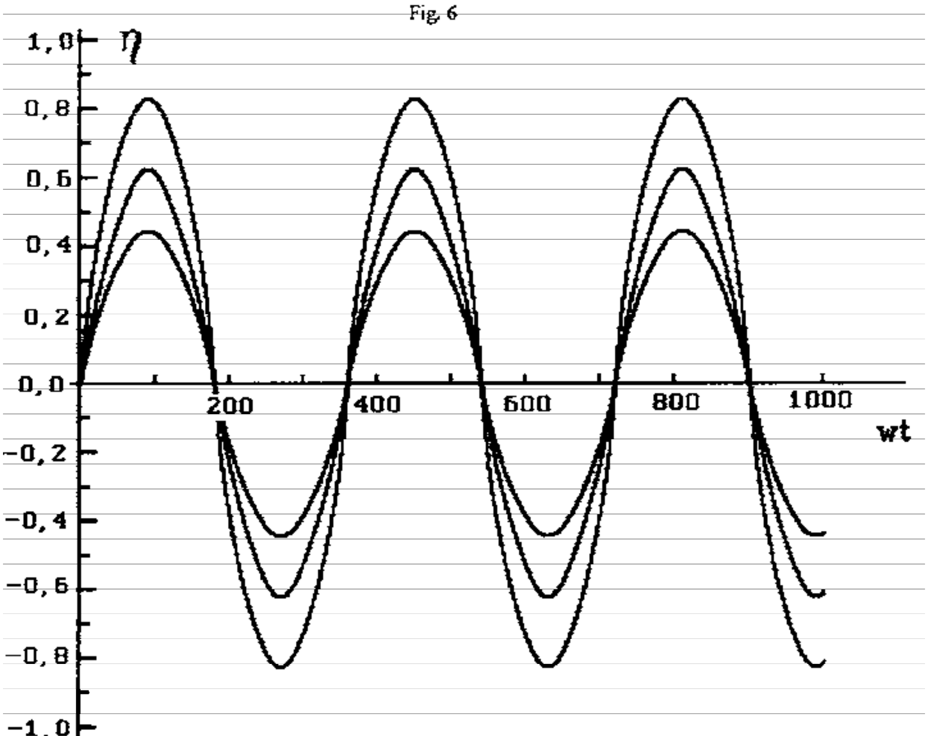

η
1,0
0,8
0,6
0,4
0,2
0,0
-0,2
-0,4
-0,6
-0,8
-1,0
200
400
600
800
1000
wt

Fig. 7

Fig. 8 and Fig. 9 show the diagram for a possible use of the combination investigated in a transforming device. The electromagnetic transducer deviates the plate and the flow is distributed into two output channels. The input low power signal is the current strength I, and the output – the difference in the pressures at the output holes.

2. Transfer and logarithmic characteristics

Electromechanical transducer

The condition for dynamic balance of the moments, acting on the transducer (Fig. 10) is

(13) $$M_I = M_m + M_h + M_{spr},$$

where M_I is the electromagnet moment; M_m – the moment of the mobile parts; M_h – the moment from the viscose friction with the plate; M_{spr} – the moment of the spring forces (the plate and the centering springs).

This equation, considering the point of hanging of the electromagnetic transducer, has the type:

(14) $$k_I\, I = m\frac{d^2z}{dt^2} + h\frac{dz}{dt} + (c_{spr} + c_{pl})\, z.$$

where m is the mass of the mobile parts, in this case – the deflector; h is the coefficient of the viscose friction of the plate in the oil, going out of the nozzles (in case such a configuration is accepted); c_{spr} and c_{pl} are spring constants.

The transducer transfer function accepting as input – the control current and output – the plate deviation, is [10]:

(15) $$W_E(s) = \frac{z(s)}{I(s)} = \frac{k_E}{T_E^2 s^2 + 2\,\xi_E T_E s + 1},$$

where

(16) $$T_E = \sqrt{\frac{m}{c_{spr} + c_{pl}}};$$

(17) $$\xi_E = \frac{h}{2\sqrt{m\,(c_{spr} + c_{pl})}};$$

(18) $$k_E = \frac{k_I}{c_{spr} + c_{pl}}.$$

The first series of the electrohydraulic servo-valves of CK-1 type produced in the country are similar transducers and the transfer function for them has the form:

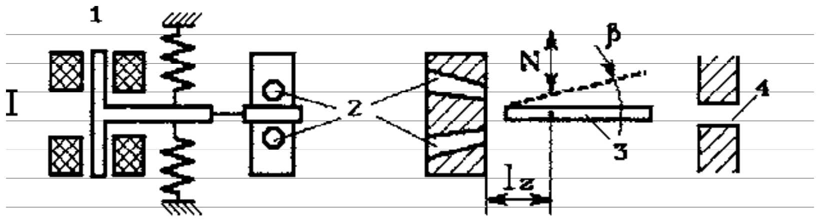
(19) $$W_E(s) = \frac{7.10^{-4}}{5.10^{-8}s^2 + 2.10^{-4}s + 1}.$$

The logarithmic amplitude-frequency characteristics has the type:

(20) $$L_E(w) = 20\lg k_E - 20\lg\sqrt{(1 - w^2T_E^2)^2 + 4\,(\xi_E w T_E)^2}.$$

The logarithmic phase-frequency characteristics is:

(21) $$\psi_E(s) = -\operatorname{arctg}\frac{2\,\xi_E w T_E}{1 - T_E^2 w^2}.$$



1 - electromechanical transducers
2 - output nozzles
3 - deflector
4 - feed nozzle

Fig. 8

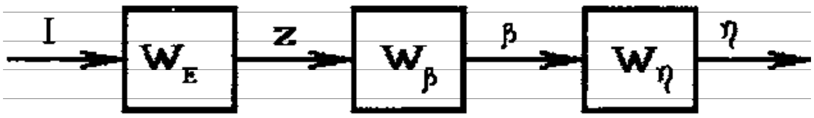


Fig. 9

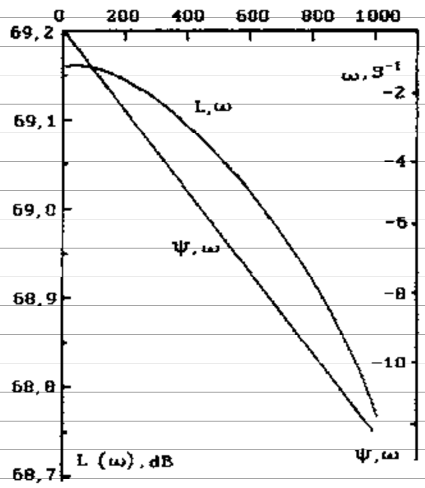


Fig. 10

For a transducer of CK-1 type with $k_E = 7.10^{-4}$ cm/mA, it is obtained:

(22) $$L_E(w) = -63 - 20 \lg \sqrt{(1-w^2\, 5.10^{-8})^2 + 4.10^{-8} w^2}\,;$$

(23) $$\psi_E(w) = -\operatorname{arctg} \frac{2.10^8}{1-5.10^{-8} w^2}.$$

The second unit (Fig. 10) is proportional, $z = l_z \operatorname{tg}\beta \approx l_z \beta$ with a transfer function (for small values of β)

(24) $$W_\beta(s) = \frac{\beta(s)}{z(s)} = \frac{1}{l_z}.$$

The logarithmic amplitude-frequency and phase-frequency characteristics are respectively:

(25) $$L_\beta(w) = 20 \lg \frac{1}{l_z},$$

(26) $$\psi_\beta(w) = 0.$$

The third unit, defined from equation (12), can be simplified developing the first term in the right side into a power series and neglecting the low order terms. It is assumed for the second term, due to the small angles of deviation ($\beta = 0 \div 6°$) that

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

Then

(27) $$\eta = \frac{4}{\pi r_0} x_k \beta\,.$$

The transfer function and the logarithmic frequency characteristics become:

(28) $$W(s)_\eta = \frac{\eta(s)}{l(s)} = \frac{4 x_k}{\pi r_0}\,;$$

(29) $$L_\eta(w) = 20 \lg \frac{4 x_k}{\pi r_0}\,;$$

(30) $$\psi_\eta(w) = 0.$$

The common transfer function will be

(31) $$W(s)_\eta = \frac{\eta(s)}{l(s)} = W_E(s) W_\beta(s) W_\eta(s) = \frac{k_E}{T_E^2 s^2 + 2\xi_E T_E s + 1} \frac{1}{l_z} \frac{4 x_k}{\pi r_0}\,.$$

The logarithmic frequency characteristics are correspondingly:

$$L(w) = L_E(w) + L_\beta(w) + L_\eta(w) =$$

(32) $$= 20 \lg k_E - 20 \lg \sqrt{(1-w^2 T_E^2)^2 + 4(\xi_E w T_E)^2} + 20 \lg \frac{1}{l_z} + 20 \lg \frac{4 x_k}{\pi r_0}\,;$$

(33) $$\psi(w) = \psi_E(w) + \psi_\beta(w) + \psi_\eta(w) = -\operatorname{arctg} \frac{2\xi_E w T_E}{1 - T_E^2 w^2}.$$

The set of equations (12)–(20), accounting the friction forces and the alteration of the motion quality, is the system of equations, defining the diagram discussed:

(34) $$k_l I = m \frac{d^2 z}{dt^2} + c_{\text{spr}}\, z + R_{\text{fr}} - R_x\,;$$

(35) $$z = l_z\, \text{tg}\beta;$$

(36) $$\eta = \frac{2}{\pi r_0^2}\Big[\, x_k\beta\sqrt{r_0^2 - (x_k\beta)^2} + r_0^2 \arcsin\frac{x_k\beta}{r_0}\Big];$$

(37) $$R_{\text{fr}} = c_f\, f\, P_x\,;$$

(38) $$R_x = \rho\, f\, u_0^2\,(\,1 - \cos\beta\,).$$

Equation (37) determines the friction force between the flow and the plate, c_f being the friction coefficient, f – the surface of the streamlined plate and R_x – the pressure, defined by the curve of pressures distribution (Fig. 2).

The friction coefficient is defined by [2].

(39) $$c_f = \frac{0{,}644}{\sqrt{R_x}} = \frac{0{,}644}{\sqrt{u_0 x_k / v}}\,.$$

Conclusion

The results obtained lead to the conclusion that the investigated effects of interaction between a flow of incompressible fluid and a plate streamlined by it can be used to design some transducer and control devices.

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Электрогидравлический усилитель с механическим отклонителем струи

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Исследуется возможность использования свободной струи несжимаемой жидкости с подвижной пластинкой для создания электрогидравлических усилителей. Исследовано обтекание тонкой пластинки. Предлагается схематическое решение усилителя. Выведены статические, передаточные и частотные характеристики.