JET ELECTROHYDRODYNAMIC SIGNAL ENERGY FROM CONVERTERS

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Signal energy from converters (from electrical to hydraulic or pneumatic or vice versa) serve to couple electrical and hydraulic (pneumatic) subsystems.

Here I survey conversion principles to give hydraulic and pneumatic signals from electrical ones, in which a jet of liquid or gas is controlled by Coulomb and polarization forces produced at the molecular level by the direct application of strong electric fields to the working media, along with the associated phenomena, which enable one to eliminate all moving mechanical or electromechanical components from the conversion and thus to raise the response rate and reliability [1-4].

Electropneumatic and Electrohydraulic Converters with Jet Turbulization. The working principle is that stability is lost and turbulence sets in at fixed distances in a sheathed laminar jet as a result of the coherent motion of the ions produced in a markedly inhomogeneous electric field transverse to the jet, which occurs when the voltage U on the electrodes is raised to a value U_c [5]. For $U_c \leqslant U < U_{1i}$, the cross section x_{t0} for the transition from a laminar jet to a turbulent one is displaced towards the nozzle and can attain the inlet section because the distance x from the forming nozzle 1 and to the receiving nozzle 6 (Fig. 1a) is less than x_{t0}. If the current (electrode voltage) increases further, the pressure p_r in the receiving nozzle begins to decrease sharply at constant supply pressure p_s because the kinetic energy of the jet is reduced on expansion and there are reverse-flow effects.

$$x = k_1 x_{t0}, \tag{1}$$

in which $k_1 = 0{,}7$—$0{,}8$.

If the forming nozzle is a long capillary tube with diameter d, for Reynolds numbers for the gas flowing in the nozzle $800 < \mathrm{Re} < 2300$ one has

$$x\left\{d\left[50{,}1 - 7{,}178\exp\left(-\frac{8{,}55\cdot 10^{-6}(p_s^2 - p_0^2)\,d^3}{\nu^2\rho^2 lRT_a}\right)\right]\right\}^{-1} = k_1. \tag{2}$$

This characterizes the relationship between the major design and gas-dynamic parameters in an electropneumatic converter with turbulence produced by an ion flux.

Such converters can be divided into types with unipolar and bipolar ion flows between the electrodes in accordance with the way in which the action on the laminar jet is organized [6, 7].

The range in p_r for $U < U_{1i}$ in excess of $0 \leqslant U < U_c$ is bounded by the pressure $p_{r\,max}$ set up by the laminar jet 2 in the receiving nozzle 6 (Fig. 1a), which corresponds to the maximum supply pressure, while there is a lower bound $U_c \leqslant U < U_{1i}$ set by the residual pressure $p_{r\,min}$ produced in the receiving nozzle by the turbulent jet.

In general $p_{r\,max} = k_2 p_r$. If the converter is coupled to a blind chamber, $p_{r\,max} = k_3 p_s$, and k_3 is usually in the range 0.4-0.6.

To reduce $p_{r\,min}$, it is best to deflect jet 2 to the drain after turbulization in the space 4 in electrohydrodyanmic conversion by the use of jet attraction to a solid wall, e.g., in the cone 5 (Fig. 1a). For an electropneumatic converter with such a cone, k_3 = 0.65-0.7.

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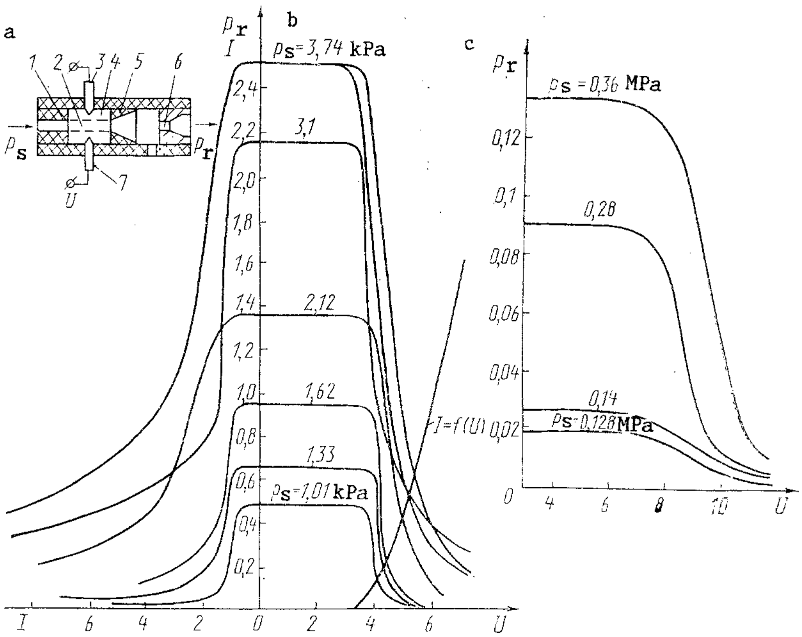

Fig. 1. General scheme (a) and static EHD characteristics for electropneumatic (b) and electrohydraulic (c) converters with jet turbulence produced by a bipolar ion flux; working media: b) air; c) transformer oil; U in kV, p_r in kPa (b) and MPa (c), I in μA (abscissa) or 10^{-5} A (ordinate).

To improve the reliability in these devices on miniaturization, we have developed an essentially new method for EHD control [7], in which (Fig. 1a) a bipolar corona discharge is produced between the electrodes 3 and 7 of needle-needle type between the forming nozzle 1 and receiving nozzle 6, whose intensity is varied by adjusting the voltage between them.

In the operation of such an EHD device, the converter may be switched frequently via various control systems. In turn, the converters can work in analog mode, If the input electrical signal (on or off one) is chosen such that the working point lies within the quasi-linear static characteristic, the transfer function in the linear approximation can be derived from the observed transient response by standard methods. For example, for an EPC with jet turbulization, which can be provided by opposing flows of ions differing in sign (Fig. 1a), the transient response as precessed by the area method gives the transfer function as

$$W(s)=\frac{\Delta p_r(s)}{\Delta U(s)}=\frac{k\,e^{-\tau s}}{T_3^3 s^3+T_2^2 s^2+T_1 s+1}. \tag{3}$$

If air is used as the medium, we have in (3) that $\tau = 0.6\cdot10^{-3}$ sec; $T_1 = 0.97\cdot10^{-3}$ sec; $T_2^2 = 0.535\times10^{-6}$ sec^2; $T_3^3 = 0.11\cdot10^{-9}$ sec^3 for switching on, and for switching off correspondingly $\tau = 0.45\times10^{-3}$ sec; $T_1 = 1.46\cdot10^{-3}$ sec; $T_2^2 = 0.94\cdot10^{-6}$ sec^2; $T_3^3 = 0.33\cdot10^{-9}$ sec^3.

We solve the third-order differential equation in (3) by Cordano's method with unit step input to get the transient response for $t-\tau \geq 0$ in dimensionles form as

$$\sigma(t-\tau)=\frac{p_r(t-\tau)}{p_r(\infty)}=1-A\,e^{-a(t-\tau)}-\{B\cos\omega_0(t-\tau)+C\sin\omega_0(t-\tau)\}\,e^{-c_1(t-\tau)}. \tag{4}$$

For an EPC with turbulence produced by oppositely directed ion flows, which can be produced by an SL-10 turbulent amplifier on the Fig. 1a scheme, one has for switching on that $A = 0.52$; $B = 0.48$; $C = 1.35$; $a = 2920$ 1/sec; $c_1 = 972$ 1/sec, $\omega_0 = 1243$ 1/sec, and for switching off correspondingly $A = 1.26$; $B = -0.26$; $C = 1.1$; $a = 1252$ 1/sec; $c_1 = 810$ 1/sec; $\omega_0 = 1243$ 1/sec.

Converters with Compact or Droplet Jet Deflection. Here a jet may be turbulent immediately after the end of the forming nozzle, which is an essential difference from the previous case. An electric field deflects the charged or uncharged jet relative to the receiv-

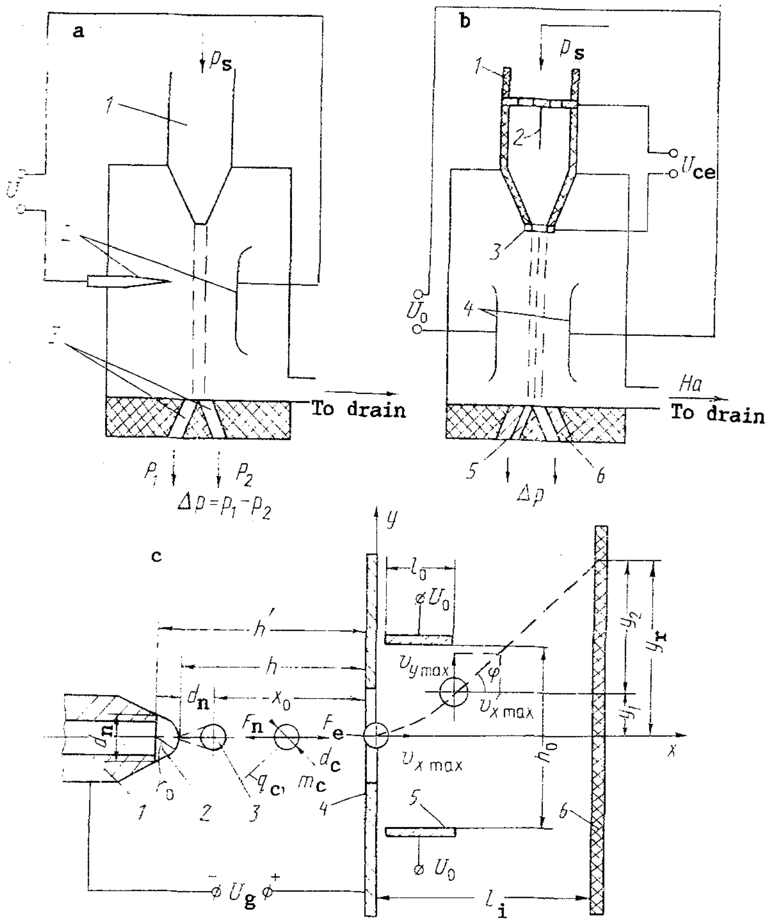

Fig. 2. Liquid jet control principles for an inhomogeneous electric field (a) with charged compact jets (b) and droplet ones (c).

ing nozzles and converts the kinetic energy $\rho v^2/2$ in a compact liquid or gas jet in particular to the potential energy of the pressure behind the reciving nozzles. In an electrodroplet recorder, the data-bearing parameter is the deflection from the initial path for a drop of ink (paint, and so on) arising from a noncompact droplet jet.

EHD control can be proportional or digital and applied with charged or uncharged sheathed or unsheathed (compact or droplet) jets. Static electrohydraulic or electropneumatic converters are used to deflect uncharged sheathed jets.

In a jet device, the liquid is deflected with respect to the receiving nozzles by the force arising between the electrodes, which receive the control voltage amplified to 1-10 × 10^3 V.

If we neglect the electrostriction, the forces acting on unit volume of a jet of insulating liquid in an electric field E will be

$$f = -0{,}5\varepsilon_0 E^2 \nabla\varepsilon + \rho_e E. \tag{5}$$

From (5) we draw three major conclusions on the deflection methods:

1) a jet in the EHD zone may be uncharged ($\rho_e = 0$) or charged ($\rho_e \neq 0$);

2) if only polarization forces are used, with $\rho_e = 0$ in (5), a jet uncharged in the absence of a voltage on the electrodes should be unsheathed, since ε in the surrounding medium should be substantially different from that in the jet to provide a gradient; and

3) if a charge is produced in advance in some way in a jet with U = 0, one can deflect a sheathed or unsheathed jet.

In uncharged unsheathed jet propagating in a weakly polarized gas (such as air), for which the dielectric constant can be taken as proportional to the density ρ to a first approximation, there are bulk forces due to EHD:

$$f = 0{,}5\varepsilon_0 (\varepsilon - 1) \nabla E^2. \tag{6}$$

We see from (6) that an uncharged unsheathed jet can be controlled by an inhomogeneous field (gradient in E), but the maximum strength must be restricted to E_c, at which a corona discharge arises:

$$E < E_c \tag{7}$$

Figure 2a illustrates the working principle for an electrohydraulic converter involving the deflection of an uncharged unsheathed jet in an inhomogeneous field. The liquid flows from the nozzle 1 in response to the supply pressure p_s and enters the atmosphere (air). Then it passes between the deflecting electrodes 2 of needle-plane type and with U = 0 enters the receiving nozzles 3, being evenly distributed between them and producing a pressure there $p_1 = p_2$, i.e., the pressure difference between the nozzles is $\Delta p = p_1 - p_2 = 0$.

When a voltage is applied to the electrodes 2 ($U \neq 0$), a markedly inhomogeneous field arises, and throughout the working range in U, (7) applies, and an unsheathed uncharged jet is deflected by the (6) force through an angle θ towards the needle electrode (attraction into the high inhomogeneity region), so the pressure p_1 in the left-hand nozzle increases (Fig. 2a), while that p_2 in the right-hand one is reduced by the same amount. One then gets the corresponding pressure difference at the output.

The static characteristic θ = f(U) is [8]

$$\theta = k_4 \left(\ln \frac{h + r_0}{r_0} \right)^{-2} \frac{\varepsilon_0 (1 - 1/\varepsilon)(d_n + 2h_1)\, l_0 U^2}{h_1^2 (d_n + h_1)^2 \mu_n^2 p_s}. \tag{8}$$

There is positive feedback from the jet position, nonlinearity in the static characteristic, and nonreversible control, which predetermine the application for the discrete conversion of electrical signals to hydraulic ones.

That signal conversion method is suitable only for liquid jets with comparatively low speeds (less than 1 m/sec) and thus of low power.

Figure 2b [9] shows the general control principle for charged jets (sheathed or unsheathed). The jet of insulating liquid is produced by the nozzle 1, and it is given a unipolar charge by the electrodes 2 and 3 of needle-plane type containing a hole. The charged jet is deflected by the deflecting electrodes 4. The pressure difference Δp between the receiving nozzles 5 is thus altered. In Fig. 2b, the 6 denotes the hydroelectric converter electrodes.

The static characteristic for an unsheathed liquid jet is

$$\Delta p = k_5 x_{out} = \frac{k_5 k_6 b l_0^2 (U_{ce} - U_c) U_{ce} U_0}{2\rho v^2 Q h_0}. \tag{9}$$

Parts a and b of Fig. 3 show the observed characteristics for an unsheathed liquid jet (transformer oil).

The static characteristic of the deflecting unit has been derived on the assumption that the passage through the ionizer 1 and 2 (Fig. 2b) gives each element in the unsheathed jet a charge q_e. If the receiving nozzles 5 are located directly beyond the exit section of the deflecting plates 4, we neglect the effects of the adjacent elements and find that the given jet element is deflected at the exit from the deflecting field by

$$x_{out} = \frac{q_e t_0^2}{2 m_e h_0} U_0 = 0{,}5 k_n U_0 t_0^2. \tag{10}$$

In principle, the design can be simplifed for deflecting a charged unsheathed jet by charging and deflecting the jet in a single electrode unit (Fig. 2a). The needle electrode is displaced parallel to the jet axis upwards, and the working voltage range is chosen to meet $U_c \leqslant U < U_{1i}$. In that case, U determines how the jet is charged by the corona discharge between the electrodes 2 (Fig. 2a) and is then deflected towards the exit edge of the planar electrode (the sign of the charge on the jet coincides with that of the potential on the needle).

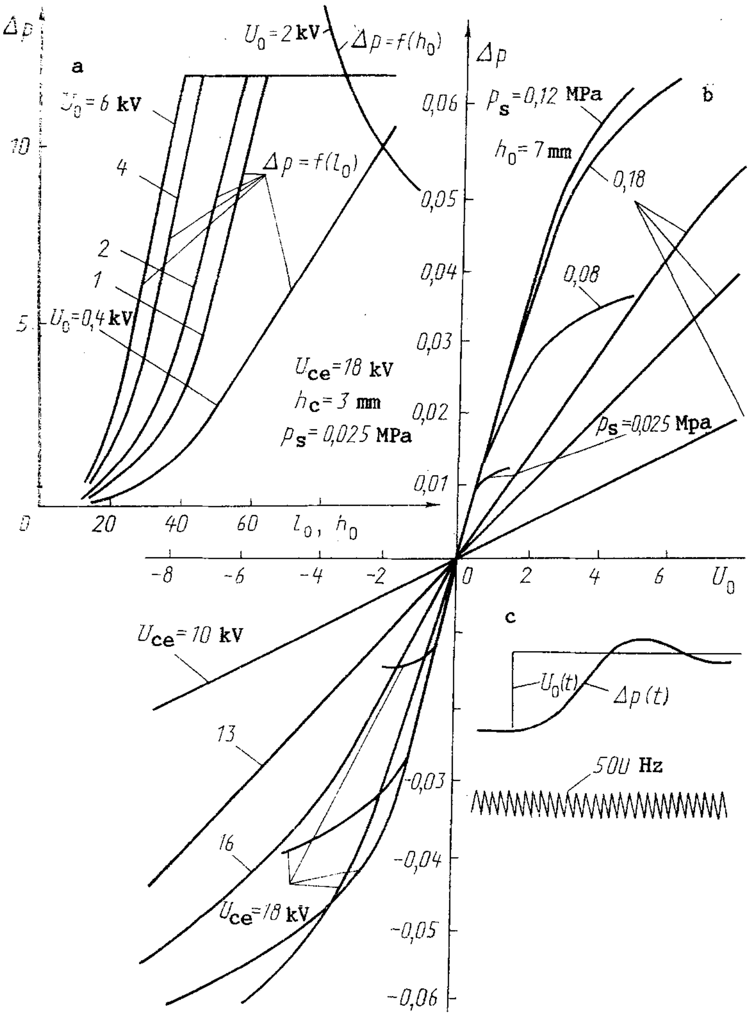

Fig. 3. Static characteristics (a and b) and dynamic characteristics (c) for EHP with unsheathed liquid jets: ℓ_0, mm; h_0, 16 mm; U_0, kV; Δp, kPa (a), MPa (b).

The static characteristic for the jet part with the deflection of a sheathed charged jet (Fig. 2b) is

$$x_{\text{out}} = \frac{m_e \rho_e U_0}{\rho h a_1} \left\{ \frac{l}{v} + \frac{m_e}{a_1} \exp\left[-\left(\frac{a_1 l}{m_e v} \right) \right] - \frac{m_e}{a_1} \right\}. \tag{11}$$

In a device for recording graphics or character data, there is a difference from the above devices in that the control object is not a compact jet but instead consists of monodisperse droplets of ink produced in a droplet generator [2]. For example, in a device with droplet emission in an electrostatic field, there is electrostatic emission for the jet 3 (Fig. 2c) because of the high potential (several kV) applied to the nozzle 1 and accelerating electrode 4. Water-based conducting liquids are used, and with $U_g = 0$ at the end of nozzle 1, there is an excess pressure (up to 1 kPa), which results in the meniscus 2 for the working liquid with radius of curvature r_0 [10]. With $U_g \neq 0$, one gets droplet emission, with the droplets acquiring charge

$$q_c = k_7 \pi \varepsilon_0 E_{cm} d_c^2 \tag{12}$$

For a water-base ink and nozzle-meniscus-plane accelerating electrodes, $k_7 = 0.34$.

A charged droplet enters the field of the deflecting electrodes 5, and U_0 determines the deflecting angle (Fig. 2c), with the droplet then falling on the data carrier 6.

Usually, the droplet charge does not vary for these modes of operation with these design parameters (q_c = const), while the data-bearing parameter is U_0, which is varied to provide the required deflection.

The resultant deflection y_r at the data carrier is as follows if aerodynamic resistance is neglected (Fig. 2c):

$$y_r = y_1 + y_2 = \frac{q_c l_0 (2l_i - l_0)}{2m_c h_0 v_c^2} U_0. \tag{13}$$

In electrostatic droplet emission (Fig 2c), (13) can be written as

$$y_r = y_1 + y_2 = \frac{U_0}{h_0}\left[\frac{q_c t_0^2}{2m_c} + (l_i - l_0) t_0 \sqrt{\frac{q_c}{2m_c U_g}}\right] = \frac{U_0}{h_0}\left[\frac{l_0^2}{4U_g} + (l_i - l_0) t_0 \sqrt{\frac{q_c}{2m_c U_g}}\right]. \tag{14}$$

In droplet emission under high pressure, a linear sequence of monodisperse droplets arises from high-frequency oscillations superimposed on the jet emerging from the shaping nozzle under the high pressure, e.g., oscillations produced by a piezoelectric converter [2]. The formation frequency f_c is equal to the frequency of the pulses at the input to the piezoelectric converter. In the zone where the droplets detach from the laminar jet, there is a charging electrode, and the charge q_c received by a droplet is proportional to the voltage U_3 on the charging electrode: $q_c = k_8 U_{ch}$.

In a high-pressure device, U_3 is usually the informative parameter, while U_0 is constant, so the (13) static characteristic is rewritten as

$$y_r = \frac{k_8 U_0 l_0 (2l_i - l_0)}{2m_c h_0 v_c^2} U_{ch}. \tag{15}$$

If the data medium in such a device lies directly at the exit from the deflecting plates, i.e., $\ell_i = \ell_0$, (13) gives the droplet deflection as

$$y_r = \frac{q_c l_0^2}{2m_c h_0 v_c^2} U_0 = \frac{q_c t_0^2}{2m_c h_0} U_0 = 0{,}5 k_e U_0 t_0^2 \tag{16}$$

for electrostatic generation, or for high-pressure generation, in accordance with (15):

$$y_r = \frac{k_8 U_0 l_0^2}{2m_c h_0 v_c^2} U_{ch} = \frac{k_8 U_0 t_0^2}{2m_c h_0} U_{ch} = 0{,}5 k_d U_{ch} t_0^2, \tag{17}$$

in which $k_e = q_c/(m_c h_0)$; $k_d = k_8 U_0/(m_c h_0)$.

With these assumptions, the static characteristics for an unsheathed compact jet (10), electrostatic droplet emission (16), and droplet emission under high pressure (17) are similar and differ merely in the transfer coefficients.

We can estimate the dynamic response from (10), (16), and (17). A stepped input $[U_0(t) = 1(t), U_{ch}(t) = 1(t)]$ gives the transient response in the deflecting device, which in general may be considered over the time interval $0 \leqslant t \leqslant \infty$, on the assumption that

$$y = 0{,}5kt^2 \quad \text{if} \quad 0 \leqslant t \leqslant t_0, \quad y = 0{,}5kt_0^2 \quad \text{if} \quad t_0 < t \leqslant \infty. \tag{18}$$

in which $y = x_{out}$ and $k = k_n$ for an electrohydraulic device, while $y = y_r$ and $k = k_e$ for an electrostatic emission device, with $y = y_r$ and $k = k_d$ for a high-pressure device.

The transfer functions are derived from (18) by applying a Carson transformation:

$$W(s) = 0{,}5ks\left(\int_0^{t_0} t^2 e^{-st} dt + \int_{t_0}^{\infty} t_0^2 e^{-st} dt\right) = \frac{k}{s^2}(1 - e^{-st_0} - st_0 e^{-st_0}). \tag{19}$$

For electrostatic production, $t_0 = l_0\sqrt{m_c/(2q_c U_g)}$, while for the deflection unit in an electrohydraulic device $t_0 = l_0/v$, and for a high-pressure device $t_0 = l_0/v_c$.

The amplitude response $A(\omega)$ and the phase response $\varphi(\omega)$ corresponding to (19) are

$$A(\omega) = k\sqrt{\omega^2 t_0^2 + 2(1 - \cos\omega t_0 - \omega t_0 \sin\omega t_0)}/\omega^2, \qquad \varphi(\omega) = \operatorname{arctg}\frac{\omega t_0 \cos\omega t_0 - \sin\omega t_0}{\cos\omega t_0 + \omega t_0 \sin\omega t_0 - 1}.$$

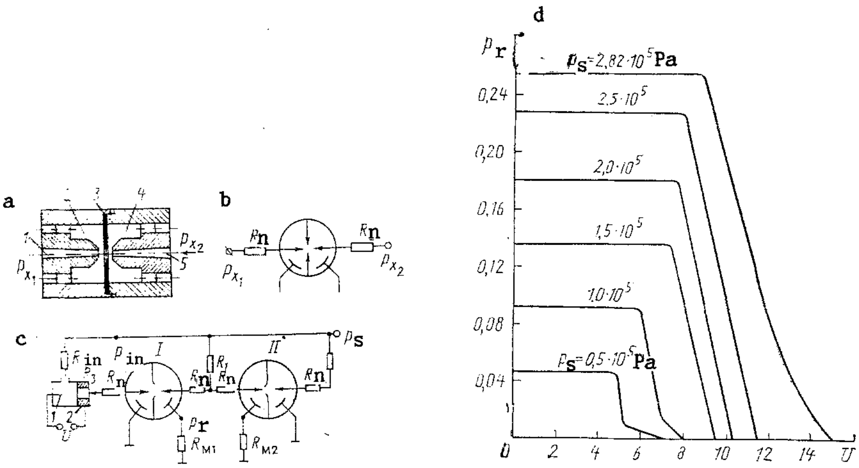

Fig. 4. Design principles for a colliding-jet converter (a-c) and static characteristics (d). U in kV and p_r in MPa.

The input harmonic signal in electrohydraulic conversion or electrostatic production is U_0, while it is U_{ch} in a high-pressure device.

The transfer function for the control chain (U_{ce} = const, Fig. 2b) for an unsheathed jet is

$$W(s) = \frac{k_{oc}}{s^2}(1 - e^{-st_0} - st_0 e^{-st_0}), \tag{20}$$

in which $k_{oc} = \Delta p / U_0$.

The transient response of an electrohydraulic converter derived from (20) agreed well with the measured one (Fig. 3c).

Electrodynamic converters with flow loading are used to control sheathed uncharged jets, with the working principle based on the flow and pressure in the working medium arising from the flow of unipolar ions in a markedly inhomogeneous electric field [11]. The static type of converter has the control voltage applied to the electrodes in the excess-pressure and negative-pressure channels, with no channel for the pneumatic or hydraulic supply, which can provide good functions and various new electropneumatic (electrohydraulic) devices with improved parameters [12].

Colliding-Jet Electrohydraulic Converters. A colliding-jet device is sensitive to any resistance change in the supply circuits to the nozzles, which facilitates EHD control. Such devices have little tendency to block with unpurified liquids, as well as low noise levels and high pressure and flow gain, so they are widely used in automatic systems.

The control principle [13] may be illustrated on the electrohydraulic converters based on colliding jets (Fig. 4, a-c).

Figure 4a shows the design of hydraulic amplifier unit with colliding jets. There are two oppositely directed nozzles 1 and 5 together with the baffle 3 having a hole separating chambers 2 and 4. The hole is on the same axis as the nozzles. The liquid is supplied with pressures p_{s1} and p_{s2} correspondingly to nozzles 1 and 5. When the jets collide, one gets a radial flow, which has an elevated pressure, and it may be compared with a liquid slide displaced by the pressure difference $\Delta p = p_{s1} - p_{s2}$ relative to the edges of the hole in the baffle. The position of that radial flow relative to the hole in baffle 3 determines p_r. Either nozzle 1 or nozzle 5 may be the EHD control channel, and either of the chambers 2 and 4 can be the collision chamber connected to the drain or the output pressure chamber.

Figure 4b shows the structure for the amplifying element, in which R_n is the hydraulic resistance of the supply nozzle, which is governed by the ratio of the pressure difference to the liquid flow.

To provide normal operation in a jet amplifier (Fig. 4a) and provide high gain, the supply pressures must be kept constant. Element I has internal negative feedback on the output pressure, so this is balanced by element II (Fig. 4c) containing colliding jets, which acts as a nonlinear hydraulic resistance.

The electrohydrodynamic control of such an amplifier is provided by EHD adjustment of the resistance in one nozzle or both simultaneously as a result of the flow of an insulating liquid in the markedly inhomogeneous field between the needle 1 and plane 2 containing a hole (Fig. 4c).

Figure 4d shows that the static characteristics are of fairly high slope, which is due to the nozzles in I and II (Fig. 4c) not being exactly coaxial in the laboratory prototype.

If the control voltage is chosen such that the device works in linear section on static characteristic on switching on and off, the transfer function in the linear approximation is

$$W(s)=\frac{\Delta p_r(s)}{\Delta U(s)}=\frac{k_{rn}e^{-\tau s}}{T_3^3s^3+T_2^2s^2+T_1s+1}. \tag{21}$$

The transfer coefficient k_{rn} is determined from the static characteristics. For example, in Fig. 4d, the linear approximation is applied for small deviations from the values taken as steady-state ones, which gives the tranfer coefficient as 19.2 Pa/V.

The time-constants T_1, T_2, and T_3 and the pure delay τ differ on switching on and off. For switching on, with transformer oil as the working liquid (type TKp), we have in (21) that $\tau = 0.8\cdot10^{-3}$ sec; $T_1 = 3.62\cdot10^{-2}$ sec; $T_2^2 + 5.12\cdot10^{-4}$ sec^2: $T_3^3 = 2.67\cdot10^{-6}$ sec^3, and correspondingly for switching off $\tau = 4.5\cdot10^{-2}$ sec; $T_1 = 1.58\cdot10^{-2}$ sec; $T_2^2 = 1.05\cdot10^{-4}$ sec^2; $T_3^3 = 0.33\cdot10^{-6}$ sec^3.

Electrohydraulic Converters Containing Spiraling Jets. A new control method based on spiraling jets [14] has been developed to increase the control sensitvity and power gain. The jet is formed as a spiral divergent cone having radial velocity v_r and rotational velocity component v_φ, while within the cone there is an electric field of variable strength, which adjusts the angle in the charged cone (Fig. 5a).

With a given relation between v_φ and v_r in the shaper 1, the liquid emerging from the hole 2 forms a jet as a hollow divergent cone 3, and with a preset exit flow rate Q_r (in the absence of the control field), the angle $2\theta_0$ for the apex of cone 3 is defined uniquely for the given v_φ and v_r. A vortex chamber may be used as the shaper 1. The hole 2 lies in the base 7, which is also an electrode. On the axis of hole 2 at a certain distance from the base 7, there is the electrode 6, which together with 7 forms an electrode pair of needle-plane type, which is the source of the markedly inhomogeneous field with strength E within the cone.

When the control voltage U_{c2}, which ranges from 0 to 30 kV, is applied to the electrodes 6 and 7 (the voltage U_{c1} on the needle 8, and plane 9 within the chamber 1 is absent), a markedly inhomogeneous field arises in the gap, so there is a unipolar ion flow with the sign of the potential of the point 6. That flow charges the liquid, which interacts with the electric field, which affects θ_1 (Fig. 5b) of the cone 3, which alters by $\Delta\theta$. This affects the flow and pressure distributions in the receiving nozzles 4.

It we neglect gravitational forces,

$$\theta_1=\theta_0+\Delta\theta=\operatorname{arctg}\left(\operatorname{ctg}\theta_0-\frac{\rho_eEx_n}{\rho v_\varphi^2}\right)=\operatorname{arctg}(\operatorname{ctg}\theta_0-N), \tag{22}$$

in which $N=\rho_eEx_n/(\rho v_\varphi^2)$.

From (22) we have two methods of control for conical jets and thus this type of jet device:

1) control of E;

2) control of the bulk charge density ρ_e, which is provided by the electrode pair 8 and 9 (Fig. 5a) of needle-plane type within the shaper 1 (with voltage U_{c1}), which is the source of the unipolar charge in the exit jet.

Two main types of this jet converter have been devised (Fig. 5a).

1. With central receiver (see hatched continuation of nozzle 5), which is a receiving tube coaxial with the shaper outlet. With $U_{c2} = 0$, the exit jet is a compact cylindrical one, and the exit flow rate is $Q_v = Q_{r\,max}$. With $U_{c2} \neq 0$, the Coulomb repulsion produces a

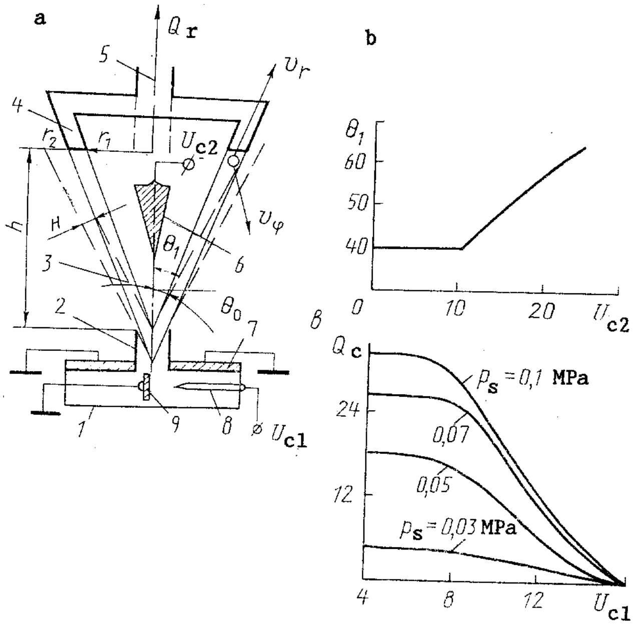

Fig. 5. Design principles for a spiraling jet device (a) and static characteristics (b and c). U_{c1} and U_{c2} in kV, θ_1 in deg, and Q_r in 10^{-6} m^3/sec.

cone from the jet, and the resultant signal is $Q_v = 0$. With this method, the Fig. 5a design does not have the conical receiver 4 and the deflecting electrodes 6 and 7.

2. With conical receiver 4, which is a special design in which the output signal is maximal for $U_{c3} = 0$ and the preliminary shaping angle $2\theta_0$ in the conical jet coincides with the angle in the receiving nozzles. For $U_{c2} \neq 0$, the conical jet is deflected, and Q_r is reduced.

The following is the static characteristic for a conical receiver if we neglect the hydraulic losses in it:

$$Q_r = \pi v_r h_2^2 \left[\mathrm{tg}^2\,\theta_1 - \left(\mathrm{ctg}\,\theta_0 - \frac{\rho_e E x_n}{\rho v_\varphi^2} \right)^{-2} \right]. \tag{23}$$

The deflection angle θ_1 in (23) corresponds to $Q_r = 0$.

Tests were made with technically pure transformer oil, which confirmed that a device having a central receiver could provide control also for sheathed jets, in contrast to a device with conical receiver. These spiral-jet devices are viable over wide ranges in hydraulic loading, which enables one to use them in pressure regulation. Also, in a device with a central receiver at $U_{c1} = 16 \times 10^3$ V, it was possible to cover the range down to zero from $Q_r = 50 \times 10^{-6}$ m^3/sec, which enables one to use the device in controlling insulating-liquid flow.

Figure 5c shows typical static characteristics for a sheathed spiral jet in which ρ_e is adjusted by the use of a vortex chamber with $\bar{p}_c = p_c/p_s = 1.2$ and $d_r = 4$ mm, with a negative polarity used with the needle within the chamber and the working point on the falling branch of the flow characteristic.

The transfer function is deived on the basis of the change in angle, the charge on the sheathed jet, and the measured transient response:

$$W(s) = \frac{\Delta p(s)}{\Delta U_{c1}(s)} = \frac{k_s j e^{-\tau s}}{(T_3 s + 1)(T_2 s + 1)(T_1 s + 1)}.$$

The dynamic characteristics are largely determined by those of the vortex chamber.

NOTATION

x, distance between shaping and receiving nozzles; x_{t0}, distance from end of shaping nozzle to cross section where laminar jet becomes turbulent; x_{out}, deflection of jet at outlet from deflecting electrodes; x_n, distance to conical receiver along surface of spiral jet; $k_1, k_2, k_3, k_4, k_5, k_6, k_7, k_8$, coefficients dependent on converter parameters; k, converter transfer coefficient; k_n, k_e, k_d, k_{oc}, k_{rn}, k_{ej}, transfer coefficients for deflecting unit in electrohydraulic converter, electric droplet producer, high-pressure droplet producer, and device with jet deflection, colliding jets, and spiral jet; d, d_n, and d_c, diameters of capillary tube, jet, and drop; p_s, p_o, and p_r, supply pressure, surrounding pressure, and receiver pressure; ν and ρ, kinematic viscosity and density; R, gas constant; T_a, absolute temperature; U, voltage; $U_{\ell i}$, U_c, U_o, U_{ce}, U_g, and U_{ch}, breakdown voltage, initial corona voltage, deflecting electrode voltage, ionizer voltage, accelerating electrode voltage, and charging electrode voltage; E, E_c, and E_{cm}, field strength, field for start of corona, and field at end of meniscus for conducting liquid at droplet formation moment; T_1, T_2, and T_3, time-constants; τ, pure delay; t_0 and t, time spent by jet element and drop in deflecting electrode field and current time; s, Laplace operator; $W(s)$, transfer function; A, B, C, a, ω_0, constants; a_1, constant proportional to the dyanmic viscosity; $\sigma(t-\tau)$, transient response; f, bulk force; ε_0, electrical constant; ε, dielectric constant; ρ_e, bulk charge density; q_e and q_c, charge densities on element of jet and drop; b, ionic mobility; θ and θ_1, angles; h, h_0, h_1, h_2, distances between electrodes, between deflecting electrodes, from end of needle to nearest surface of jet, and from end of forming nozzle to conical receiver; ℓ_0, deflecting electrode length; ℓ_i, distance from inlet edge of deflecting plates to data medium; r_0, needle electrode radius; μ_n, nozzle flow factor; v, v_c, v_φ, v_r, mean velocities of jet, drop, and rotational and radial components of velocity (liquid velocity in conical jet); Q and Q_r, volume flow rates of liquid at end of shaping nozzle and at exit from device with conical receiver; m_e and m_c, masses of jet and drop elements; y_1, y_2, and y_r, deviations of drop during time t_0, during flight from exit edges of deflecting plates to data medium, and resultant deflection; ω, angular frequency for output harmonic signal; $A(\omega)$ and $\varphi(\omega)$, amplitude and phase response characteristics; N, EHD interaction parameter.

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