Oscillatory system of the jet electromagnetic vibrator

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Abstract. The article describes the system of nonlinear differential equations of the jet electromagnetic vibrator, designed to activate Newtonian and non-Newtonian fluids. The authors formulated the principles of designing electrical and hydro-mechanical components of the device based on the viscosity and density of the process liquid. The article describes experimental frequency characteristics of the system for liquids with the different rheological properties.

1. Introduction

The problem of the alternate/reciprocal motion of the confuser in liquid continuous technological environments is of great scientific and practical interest. The technological processes of preparation of polymer fluids, cement and drilling fluids, oil-water emulsions, paints, use turbulent stream regimes of submerged jets to reduce the viscosity of extra-heavy oil and oil products. The creation of submerged jets with high shear rates results in high quality mixing, and a high degree of dispersion, which significantly reduces the time needed for certain technological processes. Sometimes, these devices may contribute to creation of a completely new consumer properties of the process fluid. All these objects are non-Newtonian and Newtonian fluids. Newtonian and non-Newtonian fluids have absolutely different behaviours, especially in dynamics [1, 2, 4].

The jet electromagnetic vibrator is a device that produces submerged jets with high shear rates (Fig. 1). Such vibrators are starting to be used in liquids preparation processes, but currently there are no methods of calculation and design of oscillatory systems with active elements making alternate/reciprocal motion in a continuous flow medium [2].

The aim of this article is to analyze the jet electromagnetic vibrator as a single oscillating system and experimental studies of the jet electromagnetic vibrator with the definition of the dependence of the resonance frequencies from the properties of process fluids.

2. Theoretical background

The electromagnet in the device is powered by half-wave current (through the diode), and creates a traction force which overcomes the elastic force and the force of the hydraulic resistance. The electromagnet armature is made as a massive anchor with nozzles through which the unidirectional submerged jets are formed [2].

The behavior of the oscillating system is described with three differential equations: the equation of the voltage balance of electrical parts of the jet electromagnetic vibrator (1); the equation of the oscillatory system motion (2); the equation of mass liquid flow through the nozzle of the vibrating activator confuser (3).

Equations (1) and (3) are not difficult to formulate [3]. The equation of activator motion (2) has a complex component, the hydromechanical force of local resistances $F_{cop}(t)$, which varies depending on the fluid velocity and the direction of activator motion.

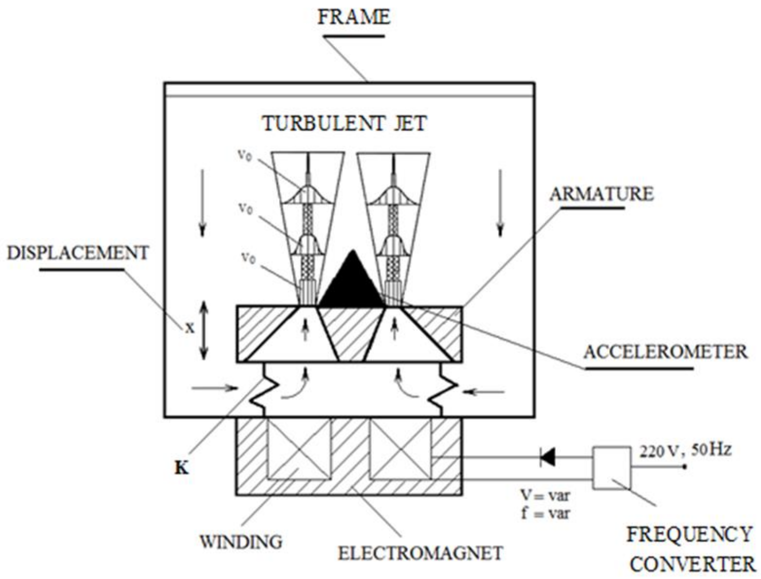

Fig. 1. Layout of the laboratory jet elecromagnetic vibrator

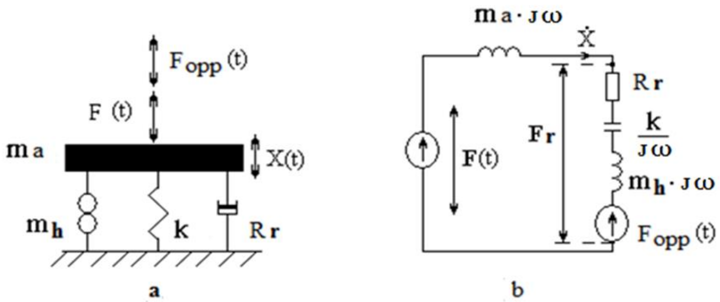

Fig. 2. Design of the Oscillatory system of the jet electromagnetic vibrator

$$U(t) = L_e(t)\frac{dI}{dt} + IR_e + I\frac{dX}{dt}\frac{dL_e}{dx} \quad (1)$$

$$F(t) = (m_a + m_h)\ddot{X} + R_r\dot{X} + K_c X + F_{cop}(t) \quad (2)$$

$$P(t) = L_g\frac{d^2m}{dt^2}\rho + R_g\rho\frac{dm}{dt} + \frac{\xi}{2}\rho\left(\frac{1}{S2\rho}\right)^2\left(\frac{S1}{S2}\right)^2\left(\frac{dm}{dt}\right)^2 \quad (3)$$

Formula (1) is the equation of the voltage balance of electrical parts of the jet electromagnetic vibrator, where $U(t)$ is the supply sine voltage, V; I is the magnet coil current, A; $L_e(t)$ is the magnet inductance, H; R_e is the magnet armature resistance, Ω.

Formula (2) is the equation of the oscillatory system motion, where $F(t)$ is the electromagnet force, N; $X(t)$ is the activator vibration displacement, m; m_a is the anchor mass, kg; $m_h = \frac{4}{3}\rho R_e^3$ is the medium added mass, kg; R_r is the active loss factor of the oscillatory system (losses in the spring, friction losses etc.), kg/s; K_c is the mechanical spring stiffness, N/m; $F_{cop}(t)$ is the hydromechanic activator motion resistance force, N.

The force of local hydraulic resistances to the activator motion will significantly depend on the geometry and dimensions of the channels through which fluids flow. The geometry and form of the channels vary depending on the changing gap between the electromagnet and the activator. The hydromechanical resistance to motion will also significantly depend on the direction of the activator movement [2].

The total hydraulic force of resistance to the forward stroke of the activator is the sum of resistance forces in the gap $F_{zaz}(\delta)$, in confuser F_{sop}, drag force F_{lob}, resistance force of the abrupt constriction of the channel $F_{s(1-2)}(\delta)$, resistance force of the abrupt enlargement of the channel $F_{r(2-3)}(\delta)$, resistance force of smooth constriction of the channel $F_{k(3)}$:

$$\mathbf{F_{opp1}}(\delta) = \mathbf{F_{zaz}}(\delta) + \mathbf{F_{sop}} + \mathbf{F_{lob}} + \mathbf{F_{s(1-2)}}(\delta) + \mathbf{F_{r(2-3)}}(\delta) + \mathbf{F_{k(3)}} + \mathbf{F_{r(3-4)}}, \mathrm{N} \quad (4)$$

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The total hydraulic force of resistance to the back stroke motion of the activator is the sum of resistance forces:

$$F_{opp2}(\delta) = F_{zaz}(\delta) + F_{sop} + F_{lob2} + F_{s(3-2)}(\delta) + F_{r(2-1)}(\delta) + F_{s(4-3)}(\delta) + F_{r(3)}, N \quad (5)$$

Formula (3) is the equation of mass liquid flow depending on the pressure under the activator and geometry of the channel, where *P(t)* is the fluid pressure under the activator, Pa; *m* is the mass of the fluid exiting the nozzle, kg; ρ is the fluid density, kg/m^3; $R_g = {128\mu L1}/{\pi d^4 l \rho^2}$, $L_g = {Ll^2}/{m_\Sigma}$, where Ll и d^4l are the equivalent length and diameter of the jet core, μ is the dynamic viscosity, Pa·s; $m_\Sigma = m_y + m_z$ is the total mass of the jet core fluid and the mass of the moving fluid in the nozzle.

The local hydraulic resistance factor depends on the nozzle design:

$$\zeta = \left(\frac{\lambda}{8\sin\alpha^l}\right)\left(\frac{n^2-1}{n^2}\right), n = \frac{S2}{S1},$$

where α is the jet taper angle which depends on the confuser (nozzle) shape.

All three equations (1, 2, 3) are nonlinear, and it is necessary to conduct a numerical or a full-scale experiment to understand the work parametres of the jet electromagnetic vibrator. According to Fig.1, the laboratory equipment was used to record frequency characteristics of the jet electromagnetic vibrator working in different technological liquids. Vibratory systems have maximum power transfer coefficients at resonance frequencies, and depending on the characteristics of the liquid these frequencies change [2, 3]. Fig. 3 shows temporal properties of the electromagnet current and vibratory acceleration of the activator at 49Hz resonance frequency when the activator is operated in water.

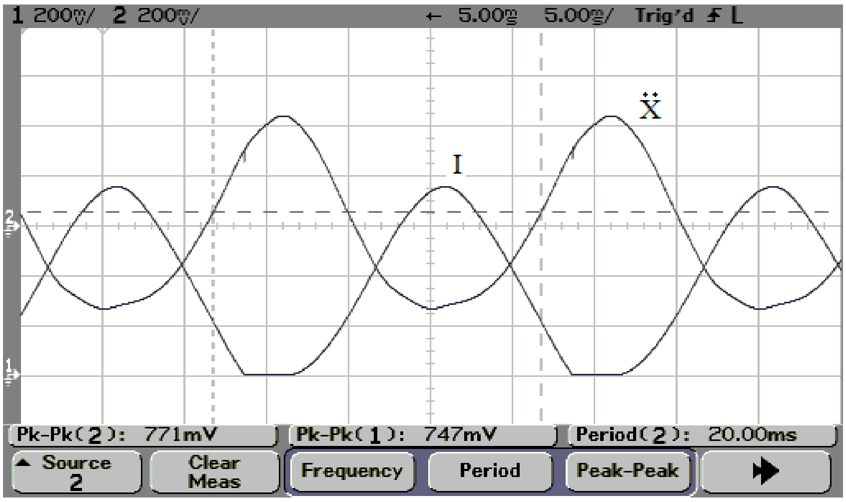

Fig. 3. Experimental temporal characteristics of the electromagnet current and vibratory acceleration operated in water. Um = 135V, Im = 3.7A, $\ddot{x}$ = 82.7 m/s^2, f = 49Hz

Fig.4 shows frequency characteristics of performance of the electromagnetic vibrator in water and in drilling agent. Fig.5 shows the frequency characteristics of the electromagnetic vibrator in cement slurries. The oscillatory systems have different resonance frequencies and different oscillation peaks, but we cannot compare these liquids because water is a Newtonian fluid, while drilling agent and cement slurry are non-Newtonian fluids and their viscosity substantially depends on the sheer speed of the fluid.

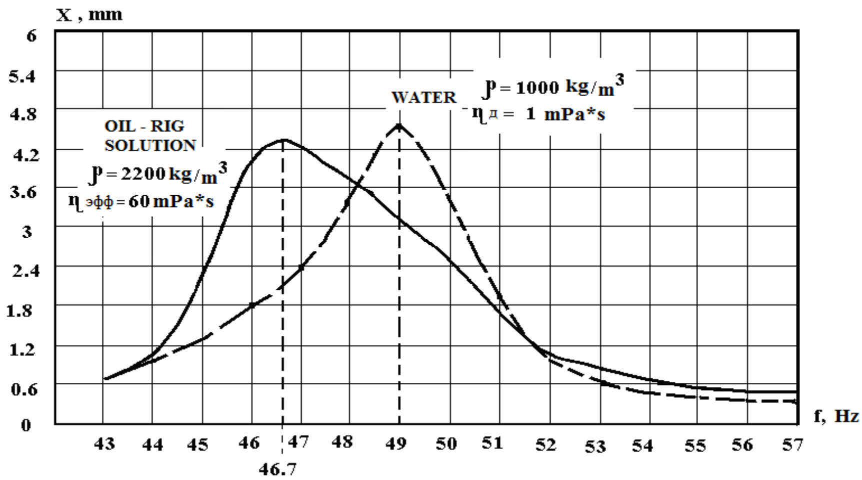

Fig. 4. Experimental frequency characteristics of performance of the activator operated in water and in drilling agent

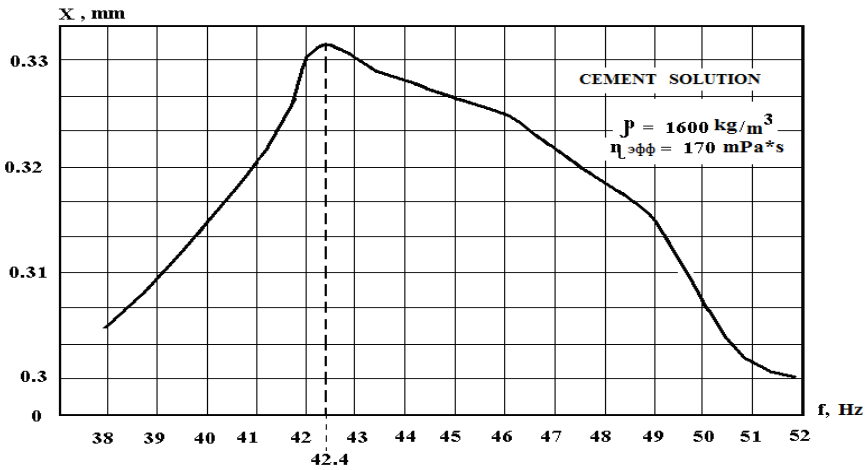

Fig. 5. Experimental frequency of the oscillatory system operated in cement slurries

3. Results and discussion

1. The oscillatory system of the jet electromagnetic vibrator is a nonlinear system, in its electrical, in its mechanical and in its hydromechanical components.
2. It is advisable to process the technological fluid in resonance frequencies of the oscillatory system.
3. The behavior of the jet electromagnetic vibrator, currents, resonance frequencies, vibration speed range and the mass flow depend on the flow properties of the technological fluid.
4. It is reasonable to design the oscillatory system and the electromagnetics of the jet electromagnetic vibrator for a specific type of technological fluids.

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