Revisiting the problem of choosing a downhole elastic wave generator for the technology of vibro-seismic impact on oil and gas deposits

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Abstract. Currently, there are no sufficiently effective submersible vibrators for the implementation of a promising technology for vibro-seismic impact on oil and gas reservoirs. In this paper, we consider the possibility of using a downhole elastic wave generator based on a two-stage centrifugal nozzle for the vibro-seismic impact technology (VSIT). The equation of non-stationary fluid flow through the nozzle has the form of a nonlinear Van der Pol differential equation. In this paper, when using the method of studying this equation in the Matlab/Simulink application package, the principal possibility of tincture of a well generator to the dominant frequency of an oil reservoir is shown. The result of the study showed that when using an automatic control system, taking into account the hydraulic flow and pressure transmission line, the elastic wave generator can be controlled by the generation frequency with the accuracy necessary for vibro-seismic action on oil and gas formations.

Keywords: hydrodynamic vibrator, centrifugal nozzle, vibration seismic effect, frequency of self-oscillations, automatic control system, nonlinear differential equations.

1. Introduction

Increasing the oil recovery of watered and late-stage fields is currently an urgent problem. Vibro-seismic impact (VSI) on oil formations by using low-frequency sources of elastic waves can be a successful method for solving this problem.

Currently VSI is used for ground-based low frequency seismo-sources: powerful stationary with vibrotractive force of $10^5$ N, or seismic vibrators with vibro-tractive force of $2 \times 10^4$ N. The main disadvantage of seismic sources surface is that the generation of surface waves takes up to 35% of the radiated energy, in addition, significant absorption of radiated seismic energy occurs in a zone of low velocity geological section, which thickness is 100-200 m [1], where up to 45% of the radiated energy is lost.

Thus, surface sources lose up to 80% of the emitted seismic energy. Some studies have shown [2] that if the sources of elastic waves could be installed under the zone of low speeds, it should be expected that their efficiency will be much higher than the surface ones. In this case, it is naturally to consider the possibility of using downhole sources of elastic waves at a depth of 100-200 m.

Many years of research based on VSI technology have allowed us to identify several basic patterns for the implementation of VSI.
- generation of elastic waves at the dominant frequency of the formation (5-20 Hz) with an accuracy of at least 0.1 Hz;
- duration of action to the formation (2-2.5 months every day, 10-12 times in sessions of 30-40 minutes each);
- the period of increasing the productivity of wells after VSI is more than 12 months.

Downhole hydrodynamic submersible vibrators for intensifying oil inflow create low-frequency pressure drops in the bottom-hole zone, while an all-round pulsating action is provided in radial direction [2]. In [2], it is shown by the figurative formulation of I. S. Chichinin that "rocks behind the well wall act as a hoop", which significantly reduces the intensity of elastic waves propagating from such vibrators.

Comparison of pulsating and oscillating sources showed [2-5] that, for example, at a frequency of 10 Hz, the oscillating source will be 150 times more efficient than the pulsating one.

There is a complex problem - converting a pulsating source into an oscillating one. In [4, 5], one of the possible approaches to solving this problem is proposed.

To convert an omnidirectional pulsating pressure drop into an oscillating action on the reservoir [4], the lower part of the oil-well tubing must have a modified design, for example, using pneumatic rubber-cord shells.

This approach makes it possible to create an alternative to powerful low-frequency ground sources of seismic waves for VSI in the area of the oil reservoir for wells with a depth of 100-200 m, i.e. beyond the low-speed zone.

The question of choosing a downhole elastic wave generator for VSI is important, since the generator must meet the following requirements:
- serviceability - 2-2.5 months;
- providing a pressure drop at pulsations of 2-5 MPa;
- ability to adjust the frequency in the range of 5-20 Hz;
- ensuring accuracy of maintaining the frequency of 0.1 Hz.

In scientific papers, a lot of works are devoted to the subject of this study. For example, in [6] it is noted that the main obstacle to the widespread use of downhole seismic technologies is the lack of a commercially available downhole seismic source. The development of an effective downhole source of seismic waves can make it attractive for the development of hydrocarbon production. It is shown that the developed prototype of a clamping hydraulic bottom-hole vibrator successfully produces direct P-waves and S-waves in the range of 10-640 Hz.

In [7], it was confirmed that the EnviroVibe vibrator, which is usually used in near-surface studies, generates high-frequency energy enough to effectively display lithological layers at a depth of 100 m.

In [8] it is shown that the underground seismic survey requires the development of more powerful downhole sources of seismic waves. The research made it possible to create an electrohydraulic source of a vertical transverse wave.

However, in paper [9] devoted to well seismology it is noted that a powerful fixed vibration source with a swinging frequency can also be used to improve the efficiency of oil production.

In [10], the use of vibration in wells to increase oil recovery by reducing capillary forces and the formation of accumulations of oil droplets in the supply fluid flow was considered.

Paper [11] is devoted to the analysis of the physical model of the downhole orbital vibrator, which is considered as a point acoustic force related to the downhole fluid.

In studies [12], it is shown that elastic waves of high frequency (about 20 kHz) have a local effect and serve mainly to stimulate the downhole zone of the well. Low frequency waves (for example, 40 Hz) can cover a large area and can be used to stimulate the formation. It is noted that surface sources are usually used for these purposes, but there are examples of using low-frequency vibrators in wells.

The work is also aimed at finding out the main mechanisms related to the use of vibration energy in complex porous structures of fluid-saturated oil layers.

In [13], the results of bench tests of various types of vibrators are presented.
Dyblenko and Kamalova [14, 15] analyze the advantages and disadvantages of various types of downhole vibrators for the purpose of vibro-wave action on the bottom-hole area of the well is given. Based on bench and field tests, the authors concluded that the best option for downhole vibrators is a hydrodynamic generator based on vortex centrifugal injectors.

Based on the information about the principle of operation, design solutions and test results, a hydrodynamic downhole generator based on vortex centrifugal injectors will be the best choice for use in VSI technology.

2. Theory
In this paper, the main attention is paid to the regulation of the frequency of elastic wave radiation by a hydrodynamic generator based on a two-stage centrifugal nozzle.

In accordance with [14-16], the schematic diagram of the elastic wave generator is shown in Fig. 1.

![Figure 1. Schematic diagram of the elastic wave generator:](image)

1 is a container with a gas volume $V$; 2 is the liquid supply from a pump with a constant pressure; 3 is a jet with a high flow rate; 4 is a jet with a low flow rate; 5 is a swirl chamber into which the liquid enters through tangential channels (in Fig.1, not shown); 6 is a flexible membrane.

As the basic principles of such device operation are fully described in [14 - 16], we would like to note that a liquid vortex occurs in the mixing chamber 5 and in if there is elasticity due to the tank with gas 1, a section with negative hydraulic resistance appears on the flow characteristic.

Such area existence suggests the possibility of self-oscillation.

The flow characteristic in [15] for this work was approximated by the following polynomial:

$$P_2 = c + aQ + bQ^2,$$

where $P_2$ is the pressure in the main line; $Q_{\text{rel}}$ is the relative flow rate; $Q_{\Sigma}$ is the total flow through the nozzles; $Q_{\text{min}}$ is the flow through the jet 4 (Fig. 1); $c = 0.94; a = 0.14; b = 0.0054$.

Equation of non-stationary liquid flow in a line with a large flow through the jet 3 (Fig. 1) has the form of a nonlinear Van der Pol differential equation [15, 16]:

$$\tau_m \frac{d^2 Q_3}{dt^2} + \left( a + 3bQ_3^2 \right) \frac{dQ_3}{dt} + \frac{Q_3}{\tau_n} = 0,$$

(2)
where $Q_2$ is the variable component of the liquid flow rate; $\tau_m = \frac{\rho \ell_2 Q_{20}}{F_2 F}$ is the inertial time constant; $\bar{Q}_{20}$ is the average volume flow rate; $\ell_2$ is the length of the main line from the jet 3 to the tank 1; $F_2$ is the area of the main pipe; $\tau_c = \frac{\rho V}{Q_2}$ is the capacitive time constant; $V$ is the volume of gas in the air chamber; $\rho$, is the density of the liquid.

The Van der Pol equation is sufficiently well studied and has a limit cycle of stable self-oscillations, while the amplitude of the flow rate fluctuations will be determined by the expression:

$$|Q_2| = 2 \sqrt{\frac{a}{3b} Q_2}$$

while the amplitude of pressure fluctuations in front of the nozzle [16] will have the form:

$$|P_2| = 2 a \sqrt{\frac{a}{3b}}$$

For the purpose of using such a pressure generator in the VSI, it is of particular interest to estimate the frequency of self-oscillations, which depends on the parameters $\mu \alpha \nu \delta$

Let us reduce equation (2) to the following form:

$$\dot{Q}_2 = \left[ a \frac{1}{Q_{20}} \left( 1 - \frac{3b}{a} Q_2^2 \right) \bar{Q}_2 - \frac{1}{V} Q_2 \right] \frac{P_2}{\rho L_2}$$

given that $P_2 \frac{F_2}{\rho L_2} = \text{const}$, let us introduce a new variable $y = Q_2 \cdot P_2 \frac{F_2}{\rho L_2}$.

Then equation (5) will take the following form:

$$\dot{y} = \left[ a \frac{1}{Q_{20}} \left( 1 - \frac{3b}{a} y^2 \right) \bar{Q}_2 - \frac{1}{V} y \right] \frac{P_2}{\rho L_2}$$

The study of equation (6) showed that the volume of the gas chamber $V$ should be chosen so that at the maximum possible flow rate for the used pump $Q$, the highest frequency of self-oscillations is 20 Hz.

The solution of the nonlinear equation (6) was carried out in the Matlab/Simulink application package. The model diagram is shown in Fig. 2.

![Figure 2. Model in Matlab / Simulink](image-url)
The dependence of the frequency of steady-state self-oscillations on the average flow rate $Q_2$ in the discharge line at $V = 10^{-4} \text{ m}^3$ and values $a = 0.14$, $b = 0.0054$ is shown in Fig. 3.

It seems necessary to study the process of self-oscillation development. For example, figure 4 presents the process of establishing self-oscillations from the initial value of the amplitude 0.5 to 6 at $Q = 2 \times 10^{-3} \text{ m}^3/\text{s}$. The study of solutions to equation (6) showed that the time $T$ of establishing self-oscillations depends non-linearly on the flow rate $Q$ and, consequently, on the frequency of self-oscillations. The result of estimating time $T$ for different values of $Q$ is shown in Fig. 5.

To build a frequency control generator based on a two-stage vortex nozzle, the generator can be represented in the first approximation as a sequential connection of the aperiodic link with the time constant $T(Q)$ (Fig. 5) and the inertia-free link $f(Q)$ in accordance with Fig. 3.

![Figure 3. The dependence $f(Q)$](image1)

![Figure 4. Development of self-oscillation](image2)
It should be noted that the use of an elastic wave generator for the purposes of VSI has the following feature: after determining the dominant frequency of the reservoir by geophysical methods, the generator must be configured to this frequency and within 2-2.5 months in intermittent operation mode, it must maintain this frequency with an accuracy of 0.1 Hz.

As a result, one of the possible options for the frequency tuning sequence can be the manual tuning mode for the dominant frequency and automatic frequency stabilization.

In this case, for the aperiodic link, constant $T_2$ is selected in accordance with the curve in Fig. 5, while the inertial link in a small neighborhood of the tuning frequency can be represented by a proportional link $\Delta f = K_3 \Delta Q$, where $K$ equals the tangent of the tangent angle at the tuning point.

The basic block diagram in the assumption of the ideal operation of the dynamic pressure sensor and the frequency meter for controlling the frequency of the generator is shown in Fig. 6.

We assume that the transfer function of the flow regulator has the following form:

$$W_i(p) = \frac{K_1 \cdot K_2}{p(T_i p + 1)}$$

where $K_1$ is the gain ratio; $K_2$ is determined by the parameters of the electric motor, gearbox and the area of the throttle opening in the flow controller. $W_i(p)$ is linear in ideal working pressure regulator of the pump; $W_3(p)$ is the transfer function of the hydraulic lines from the pump to the generator; $W_4(p)$ is the transfer function of the hydraulic lines from the generator to the wellhead.

To control the frequency of the generator pressure drop, it is necessary to change the flow rate at the beginning of the line length $l = H$, where $H$ is the depth of the well, and the frequency measurement takes place at the wellhead.

![Diagram](image-url)
**Figure 6.** Basic block diagram:

Q1 – flow rate at the pump outlet; Q2 - flow rate at the generator; ΔP – pressure drop created by the vibrator; f3, f – set and measured frequency; W1 (p) - transfer function of the flow controller with the spool drive; W 2 (p) – transfer function of the hydraulic line; W 3 (p) - transfer function of the generator; W 4(p) - transfer function of the frequency meter

The hydraulic scheme of this system presupposes that there are no reflections of perturbation waves from the ends of the lines (for the first line by Q(t), for the second – ΔP(t)), since the lines pass the flow of the medium that is transferred by a straight wave. Thus, we can assume that the loads connected to the ends of the lines are consistent. In this case, the following expressions can be obtained [17]

\[
\frac{Q_2(p,t)}{Q_1(p,0)} = e^{-\delta t} \quad \text{for the flow transfer line.}
\]

\[
\frac{\Delta P_1(p,0)}{\Delta P_2(p,t)} = e^{-\delta t} \quad \text{for the differential pressure transmission line.}
\]

Assuming the quasi-stationary nature of the hydraulic resistance of the line according to [12], we can write

\[
\begin{align*}
\delta_1(p) &= \frac{P}{C_l} \\
\delta_2(p) &= \frac{P}{C_i}
\end{align*}
\]

(7)

where $C_i = \sqrt{\frac{Bf_r}{\rho}}$ is the speed of the perturbation wave propagation; $\delta \approx \frac{4\nu}{r_0^2} \sqrt{\frac{\rho}{B_1}}$ is attenuation rate; $\nu$ is the kinematic viscosity; $\frac{1}{B_i} = \frac{1}{B} + \frac{1}{E_i}$; $\nu$ is reduces modulus of the pipe elasticity; $B$ is the modulus of volume elasticity of the medium; $E_i = \frac{E \cdot \delta}{2r_0}$; $E$ is the modulus of the pipe wall elasticity; $r_0$ is the radius of the pipe; $\delta$ is the thickness of the pipe wall.

Thus, the transfer functions $W_3(p)$ and the pressure drop from the radiator to the mouth of $W_5(p)$ will have the following form:

\[
\begin{align*}
W_1(p) &= e^{-T_1 \cdot p} \\
W_3(p) &= K_i^* \cdot e^{-T_1 \cdot p}
\end{align*}
\]

(8)

where

\[K_i^* = e^{-\delta t}, \quad T_1 = \frac{\ell}{C_l}.
\]

Taking into account the above factors, the block diagram of the control system will have a form (Fig. 7), with two links of net delay according to [18] combined into one link of delay.
The analysis of a stable control system in Fig. 8 showed that for \( H = 0 \), the value \( K = K_1 K_2 K_3 \) should be \( K \leq 20 \).

At a well depth of 150 m, the effect of the delay line reduces the stability of the system and the value will be \( K \leq 4.75 \). Given that the wave generation frequency stabilization system, the astatic error will mainly be determined by the frequency measurement error at the wellhead, and given the low-frequency range of operating frequencies and the accuracy of modern measurement systems, it is not difficult to provide a frequency error of 0.1 Hz.

The analysis of the nonlinear Van der Pol equation, which describes the dynamics of the variable flow rate of the generator, allowed us to find the dependence of the frequency of self-oscillations on the flow rate of the pump on the input line with constant pressure support for a given volume of the gas chamber.

The nonlinear dependence of the self-oscillation frequency on the flow rate obtained in this paper is the basis for building a system for automatic controlling the frequency of elastic wave generation.

As a result of the analysis of Van der Pol equation in the Matlab/Simulink application package, a nonlinear dependence of the time for establishing self-oscillations \( T \) depending on the flow rate is obtained. In this paper, we consider the mode of increasing the frequency of self-oscillations, which is equal to the dominant frequency of the formation with the system of automatic stabilization of this frequency.

Further research assumes that the automatic frequency control system will also provide tuning to the specified frequency.

3. Conclusion
The conducted research has shown that for the purposes of VSI in specially equipped wells with a depth of 50-200 m, it is advisable to use generators based on two-stage vortex injectors as emitters of elastic waves. The analysis of the wave generation frequency depending on the volume of the gas chamber and the flow rate in the discharge line showed the possibility of developing a stable automatic frequency control system.

When using the developed hydrodynamic generators based on vortex injectors, it is necessary to make structural changes in terms of increasing the volume of the gas chamber to ensure the required frequency range.

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