Study of pneumatic sources of elastic waves for marine seismic exploration

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Abstract. An extensive use of geophysical methods necessitates the development of new methods and improvement of existing methods for seismic exploration to provide reliable data on the structure of the environment in difficult geological conditions. Therefore, it is especially relevant to solve the problems arising in marine petroleum geophysics, which require constant improvement of the methodology and technology of work, and the development and implementation of the advanced seismic equipment. Pneumatic sources that use compressed air as a working medium are among the most effective non-explosive sources for marine seismic exploration. Pneumatic sources exhibit high-energy characteristics, reliability and versatility. Compressor equipment that provide pneumatic sources with high-pressure compressed air is relatively easy to embed into the marine vessel’s power system. The above requires the development and improvement of theoretical methods for studying dynamic problems of a liquid half-space with buried sources of various types. A theoretical description of the formation of an elastic signal in water is given in a number of works. However, the authors of these works do not perform the analysis of gas transportation. The paper considers a number of characteristics of gas flow at a subsonic speed along the high-pressure hose from a vessel’s compressor unit to a pneumatic source. The airflow rate in the receiver-pneumatic source system is determined, and the friction force at a quasi-steady isothermal mode of gas flow is calculated. The paper presents recommendations for planning geophysical works.

1. Introduction

The development of marine seismic exploration all over the world is accompanied not only by a constant increase in the volume of work, but also by a continuous improvement of the apparatus and methodological complex, including sources [2,5].

Pneumatic sources that employ compressed air as a working medium are among the most effective non-explosive sources for marine seismic exploration. Pneumatic sources exhibit high-energy characteristics, reliability and versatility. Compressor equipment that provide pneumatic sources with high-pressure compressed air is relatively easy to embed into the marine vessel’s power system.

The development of advanced marine sources requires the formulation and solution of a wide range of problems, in particular, assessment of the efficiency of various types of sources, study of the parameters that relate the wave field characteristics to the source characteristics, theoretical analysis of various source schemes, and many others.

The above requires the development and improvement of theoretical methods for studying dynamic
problems of a liquid half-space with buried sources of various types.
A theoretical description of the formation of an elastic signal in water is given in a number of works [1–5]. However, the authors of these works do not perform the analysis of gas transportation. This is relevant since the stated time of filling the source with air to the operating pressure makes it possible to organize the work so that the seismic survey vessel moves at an optimal speed between the intervals of the source operation.

2. Determination of the airflow rate in the receiver–pneumatic source system
Figure 1 presents a block diagram of the gas flow at a subsonic speed along the high-pressure hose from the vessel’s compressor unit to the source.
The adiabatic and isothermal steady gas flow along a long cylindrical pipeline is discussed in detail in [V.N. Pogorelov, 1971]. However, neglecting wave processes, the gas flow in a pneumatic installation is considered as unsteady.

![Diagram of gas flow](image)

**Figure 1.** Determination of the airflow rate in the system: 1 – air receiver; 2 – pneumatic source; S – section of a high-pressure hose; ℓ – length of a high-pressure hose.

Neglecting a change in pressure corresponding to a change in the flow strength [N.A. Charny, 1961; G.N. Abramovich, 1969], derive the equation of flow:

\[
\begin{align*}
-\frac{\Delta P}{\Delta x} & = \frac{\Delta (pW)}{\Delta t} + \frac{\lambda}{\delta} W |(\rho W)| \\
-\frac{\Delta P}{\Delta t} & = C^2 \frac{\Delta (pW)}{\Delta x}
\end{align*}
\]

(1)

where \( P \) – gas pressure;
\( W \) – gas rate;
\( \rho \) – gas density;
\( \delta \) – hydraulic radius of a high-pressure hose;
\( \lambda \) – dimensionless characteristic of hydraulic resistance, function of size, shape and roughness of the high-pressure hose;
\( C \) – specific heat capacity.

In order to complete the system of equations (1), it is necessary to add the ideal-gas equation of state:

\[
\frac{p}{p} = RT
\]

(2)

where \( R \) – the universal gas constant equal to 8.314 J/(K mol);
\( T \) – absolute gas temperature equal to 273.15 K, and the equation of heat inflow in polytropic
thermodynamic process, where the specific heat capacity of gas is constant, i.e. C-const:

$$C^2 = n \frac{p}{p}$$  \hspace{1cm} (3)

where  \( n = (C - C_p)/(C - C_v) \) – polytropic exponent.

Assume that the gas temperature along the high-pressure hose is constant, therefore, the gas flow in the system is isothermal (n=1), then

$$\frac{p}{p} = C^2 = \text{const.}$$

Based on the above, derive the system of equations of gas flow in a long pipeline at a subsonic flow rate, which consists of three equations for three unknown functions P, p, W:

$$\begin{cases} \frac{\Delta p}{\Delta x} = \frac{\Delta (\rho W)}{\Delta t} + \frac{\lambda}{\beta} W(\rho W) \\ \frac{\Delta p}{\Delta t} = C^2 \frac{\Delta (\rho W)}{\Delta x} \\ \frac{p}{p} = C^2 = \text{const.} \end{cases}$$  \hspace{1cm} (4)

Let us introduce the boundary and initial conditions.

When considering the unsteady process of gas transportation, assume that there was no gas flow until \( t = 0 \), i.e. P and W for \( t \leq 0 \) do not depend on time.

The initial conditions are as follows:

$$W = W_{(0)} = P_{(0)} = P_0$$  \hspace{1cm} at \( t \leq 0, \ 0 < x < \ell \),

where  \( \ell \) – length of the high-pressure hose.

The boundary conditions are determined by the nature of flow disturbances at the boundary of the high-pressure hose. In the general case, the conditions represent two specified functional time dependences at \( x=0, \ t>0, \ P=P_0 \).

Let us derive the boundary condition for the hose end \( x = \ell \), where a pneumatic source with the volume of the working chamber \( V_k \) is connected,

$$P_{|x=\ell} = P_k$$,  \hspace{1cm} according to the equation of state:

$$P_k = \frac{RT}{V_k} G,$$  \hspace{1cm} (6)

where  \( G \) – weight amount of gas in the working chamber of the source.

Take the time derivative of both sides of equation (6):

$$\frac{\Delta p_k}{\Delta t} = \frac{RT}{V_k} \frac{\Delta G}{\Delta t}$$  \hspace{1cm} (7)

Weight amount of gas in the working chamber of the source  \( G = G_1 + G_2 \)

where  \( G_1 \) – gas inflow into the chamber,  \( G_2 \) – gas outflow from the chamber per unit of time,  \( G_1 = gS(\rho W), \) where  \( S \) – the cross-sectional area of the high-pressure hose.

Thus, we can write

$$\frac{\Delta P_k}{\Delta t} = \frac{RT}{V_k} S(\rho W) - \frac{RT}{V_k} G_2.$$

Taking into account the system of equations (1), we obtain:

$$\left( \rho W \right) + \frac{V_k}{S} \frac{\Delta (\rho W)}{\Delta x} = \frac{c^2}{gS} G_2,$$  \hspace{1cm} (8)

which is the required boundary condition at the end of the high-pressure hose at  \( x = \ell \).
The analytical solution of equations (1) is given in [6].

3. Calculation of the work of the friction force in a quasi-steady isothermal mode of gas flow

Let us write the work of friction forces per unit of time as [A.N. Bogomolov and others, 1965]

\[ A = \xi x \ell V, \]  

(9)

where \( \xi \) – specific friction force;
\( x \) – perimeter;
\( \ell \) – length of the high-pressure hose
\( V \) – rate established along the entire length of the hose for a given moment \( t \).

The friction force in a turbulent flow can be written as

\[ D = E F G \cdot A I, \]  

(10)

where \( E \) – specific gravity of gas;
\( J \) – Darcy factor.

Rewriting equation (9) for a circular hose with a diameter \( d \), we find:

\[ A = \pi d \ell \xi V. \]  

(11)

According to the equation (Darcy), we have:

\[ P_0 - P_k = \psi \frac{\ell}{d} \cdot \gamma \frac{V^2}{2q} = 4\xi \frac{\ell}{d}, \]  

(12)

where \( P_0 \) – pressure in the initial section of the hose;
\( P_k \) – pressure in the end section of the hose, which is equal to the gas pressure in the working chamber of the pneumatic source.

The Cliperon-Mendeleev equation of the state of gas in the working chamber of the pneumatic source can be written as

\[ P_k = \frac{G_k}{V_k} RT, \]  

(13)

where \( G_k \) – weight amount of gas in the working chamber of the source;
\( V_k \) – volume of the working chamber.

Since the weight flow rate of gas \( G_k \) in the high-pressure hose per unit time is equal to the rate of change in the weight amount of gas in the working chamber of the source, we can write:

\[ \frac{dG_k}{dt} = G. \]  

(14)

Taking into account equation (8), we write:

\[ \frac{\sigma}{\xi} = \sqrt{\frac{(P_0^2 - P_k^2)\gamma}{\psi \left(\frac{\ell}{d}\right)^2 + 2 \ln \left(\frac{P_0}{P_k}\right) \gamma RT}}. \]  

(15)

In the presence of local resistances, the reduced length \( \psi(\ell/d) \) goes into \( \psi(\ell/d) \), which is taken from the tables [V.S. Yablonovsky, 1961]

Taking into account equations (13) and (14), we find:
\[
\frac{dP_k}{dt} = G \frac{RT}{V_k} = \frac{RT}{V_k} S \sqrt{\frac{(P_0^2 - P_k^2)\psi}{\psi\left(\frac{1}{\varphi}\right)^{+2ln(P_0/P_k)RT}}}. \quad (16)
\]

It is known that the gas flow at subsonic rates in long gas pipelines is \(\psi(t/d) \gg 2ln(P_0/P_k)\), therefore, neglecting \(2ln(P_0)\) and integrating equation (16), we obtain:

\[
P_k = P_0 \sin(\omega t + B), \quad (17)
\]

where

\[
\omega = \frac{s}{V_k} \sqrt{\frac{RT_k}{\psi(\varphi)}}. \quad (18)
\]

With regard to (12) and (17), it is possible to determine the specific friction force \(\zeta\).

Since the gas flow rate along the hose is constant \((G = V\gamma S = \text{const.})\), then

\[
(V_k /RT) \cdot (dP/dT) = G = V\gamma S. \quad (19)
\]

From this equation, we find \(V\):

\[
V = \frac{V_k}{\sin(\omega t + B)} \cdot \frac{dP}{dt}. \quad (20)
\]

Now the work of the friction force per unit of time is determined:

\[
A = \pi d \ell \varphi = P_0 V_k \omega c t \pi (\sin(\omega t + B) - 1). \quad (21)
\]

or during the filling of the source to the operating pressure:

\[
A = P_0 V_k \int_0^{\pi/2} (\cos(\varphi) - \cos(\varphi)) d\varphi \quad (22)
\]

where \(\varphi = \omega t + B\).

Performing the integration, we find:

\[
A = P_0 V_k \left(\frac{P_k}{P_0} \ln \left(\frac{P_k}{P_0}\right) - 1\right). \quad (23)
\]

Taking into account that the potential energy of the working volume of the source with compressed gas under pressure \(P\) is \(PV/(k-1)\), where \(k = Cp/Cv\), we obtain the work efficiency equation:

\[
\eta = \frac{1 - \left(\frac{P_k}{P_0}\right)}{(k-1)ln(P_k/P_0) + (2-k)\left(1 - \frac{P_k}{P_0}\right)}. \quad (24)
\]

In the previous calculations, the assumption of the instantaneous establishment of the rate along the length of the high-pressure hose is of relevance. This made it possible to obtain a simple work efficiency equation, where it does not depend on the initial and final pressure values and on other process parameters. All other parameters \((V_k, \ell, d)\) determine the filling time of the pneumatic source \(T_0\) equal to

\[
T_0 = \frac{\pi}{2\omega}, \quad (25)
\]

where \(\omega\) is defined by equation (18).

Thus, the stated time of filling the pneumatic source with compressed gas to the operating pressure makes it possible to determine the optimal speed of the seismic survey vessel along the profile with the maximum daily productivity.

In addition, an important factor is the planning of the density of explosion points and the reception of seismic vibrations, which are located, for example, after 50 m when carrying out geophysical work in water areas.
Let us consider two examples.

1. When filling the source with compressed gas for 25 seconds, the vessel’s speed along the profile is 2 m/s, which corresponds to 4 knots or 7.4 km/h.
In this case, the vessel can cover about 178 km per day.

2. When filling the source for 35 seconds, the vessel’s speed along the profile is 1.43 m/s, which is 2.86 knots or 5.3 km/h.
In this case, the vessel can cover 127 km per day.
In the first case, all other things being equal, the daily productivity is 51 km higher than that in the second one.

Both cases show that a high productivity is never achieved, since the seismic survey vessel towing the receiver never moves exactly along the calculated profile due to currents and wind drift.

Therefore, when planning work, it is necessary to know in advance the density of measurements, the volume of pneumatic sources used, and the number and capacity of the compressors installed on the vessel.

4. Conclusion and recommendations
- An important factor in marine seismic exploration is planning the density of explosion points and the reception of seismic vibrations.
- The optimal speed of the seismic survey vessel depends on the time needed for filling the pneumatic source with compressed gas to the operating pressure.
- Geophysical work in water areas depends on the volume of used pneumatic sources, and the number and capacity of compressors installed on the vessel.

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