Synthesis of group compressed-air sources for marine seismics

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Abstract. The improvement of geological efficiency of marine seismic survey implies continuous improvement of the entire technological complex used in water areas. This is typically accomplished by using complex linear or spatial non-uniform compressed-air groups. In the development of such sources, in addition to solving a number of purely technical problems related to their placement on board the ship and safe operation, one of the most difficult tasks is to determine the initial requirements for selection of the main parameters of the group, such as the volumes of working chambers sources and geometry of their grouping, as well as other factors determining amplitude, time and frequency of emitted acoustic signals. This study considers the main principles of grouping the compressed-air sources for marine seismic survey. It is shown that the most important factors determining the choice of source parameters and specific research technology include the nature of geological tasks and seismic conditions, which primarily depend on the sea depth in the study area. A simple method of calculating the configuration of linear subgroups with fluctuation suppression is described, as well as examples of building linear and spatial groups based on them with pronounced directional properties are considered.

1. Introduction

The improvement of geological efficiency of marine seismic survey implies continuous improvement of the entire technological complex used in water areas. At the same time, along with the use of modern geophysical vessels, satellite positioning systems and digital seismic telemetry systems, it is necessary to use sufficiently powerful sources that excite high-amplitude and broadband signals, which are not complicated by oscillations and solve complex geological tasks in different seismogeological conditions.

This objective is usually achieved by the use of complex linear or spatial non-uniform compressed-air groups, which sometimes contain dozens of pneumatic radiators combined in a number of close subgroups – clusters [1, 9, 11]. In the development of such sources, in addition to solving a number of purely technical problems related to their placement on board the ship and safe operation, one of the most difficult tasks is to determine the initial requirements for selection of the main parameters of the group, such as the volumes of working chambers sources and geometry of their grouping, as well as other factors determining amplitude, time and frequency of emitted acoustic signals [1, 9, 11].

This paper considers some principles of construction of linear and spatial groups of compressed-air sources for marine seismic survey.

2. Tasks of selecting source characteristics during marine seismic survey
Similar to ground seismic survey, during marine seismic survey the selection of source characteristics is fully determined by the geological task, for which the on-board seismic survey equipment is created, as well as by technological peculiarities of seismic survey operations in different seismogeological conditions and capacities of the used vessels.

Thus, relatively big research geophysical vessels on a displacement of several thousand tons equipped with the powerful compressor and specialized lifting equipment necessary for exploitation of large areal compressed-air groups consisting of several (from 4 to 8) identical linear subgroups with the total volume of working chambers from 40–50 dm$^3$ to 100 dm$^3$ (and sometimes more) are most often used to solve the geological tasks related to search and exploration of deep-seated hydrocarbon fields in a shelf zone with the sea depths of over 10–20 m. In recent decades, third-generation research vessels – the so-called “ramforms” with advanced seismic equipment, which allows simultaneous registration of seismic information from several thousand channels located in several dozens of simultaneously towed streamers, have been used for 3D marine seismic survey. At the same time the most powerful areal groups consisting of 6–8 simultaneously towed streamers with the total number of pneumatic radiators reaching hundreds are used.

At a towing speed of 4–6 knots, which is typical for operations with floating piezo-streamers, it takes 8–12 s for such a vessel to pass the interval between excitation points of 25 m. The capacity of the compressor station should ensure guaranteed filling of all working chambers of group radiators with compressed air at the operating pressure of 12–15 MPa, with all compressed air energy stored per exposure may reach several (2–4) megajoules.

Thus, on the one hand the total volume of the group is determined by the capacity of the compressor station and, on the other hand, by the need to ensure such a density of acoustic energy flow in a given frequency band and in given spatial angles that provide the required signal-to-interference ratio at the input of the towed receiver, i.e. the necessary noise immunity of the group thus ensuring successful solution of the geological task.

In case of detailed seismic survey of objects limited in area lying at medium depths, specialized geophysical vessels of the second generation with displacement of up to one and a half thousand tons are used more often during profile 2D works, which have significantly less energy capacity and allow simultaneous use from 2 to 4 linear subgroups with the total number of radiators of up to 20–30, with the total volume of chambers of up to 30–40 dm$^3$. A good example in such conditions are twin-hulled ships, such as the Searcher [8], which, at low settlement (about 1.5 m) ensure the operation of similar radiating systems.

Until the late 1980s, geophysical vessels often used compact compressed-air groups with grouped radiators placed on towed metal frames. Compared to linear and even more spatial sources, compact groups have a significantly higher level of mutual acoustic influence, have weak directional properties and with the same total volume are usually inferior to linear groups in all acoustic indicators [1, 4].

Relatively small geophysical vessels with the displacement of up to 600–800 t are usually used to solve engineering-geological tasks during the study of shallow lying thicknesses and the top part of a section. As part of a technological complex that has recently operated in JSC Yuzhmorgeologia, in CJSC ROMONA, etc. [7], along with popular seismoacoustics, side-scan sonar and other methods, high-resolution high-frequency seismic survey is often used with the registration in the frequency band from 20–30 to 300–400 Hz. At the same time, the best results were obtained when relatively small compact compressed-air groups containing 3–5 radiators (1–2 clusters) with a total volume of up to 2–3 dm$^3$, and towed at a depth of 2–3 m are used as excitation sources [7].

At seismic exploration in the conditions of shallow water if the sea depth is from 2 m to 8–10 m, relatively shallow low-tonnage vessels, which specific power and loading capacity allow operating only very small compressed-air groups (8–16 radiators) with the total volume of 10–20 dm$^3$, are usually used [1, 4]. Until recently, in similar seismogeological conditions the so-called “yo-yo” technology with periodic uncoiling – streamer sampling at continuous movement of a vessel are used. In recent decades, with the advent of modern digital telemetry systems such as BOX, ARAM ARIES
and others, spatial surveillance systems with fixed bottom receivers and mobile explosion point [6] have become common on the shallow sea with the “yo-yo” technology no longer being applied.

In the most complex seismogeological conditions of the limit shallow water and in the transit zone spatial observation systems with a fixed receiving device (bottom telemetry, bottom streamer, or geophones installed on metal pins) and a mobile explosion point moving along a given network of excitation points are widely used in recent years [4]. Relatively small groups of pneumatic radiators installed on small-size floating facility (pontoon, barge, etc.) and towed on floats with suspension at a depth of 1.0–1.5 m, or moved by dragging along the bottom at a sea depth of less than 1.0 m are usually used as sources (Figure 1). In the latter case, the required information may be accumulation.

![Figure 1. Towed pontoon with compressed-air sources [1, 4]](image)

In the transit zone at the sea depth of less than 0.5–1.0 m where excitement in a water layer becomes inefficient, the best results are achieved with the use of submersible compressed-air sources exciting signals in small wells and usually working in the accumulation mode. At the same time the whole equipment set, including seismic station, compressor and auger drill or hydraulic monitor, is placed on amphibious class vehicles with increased cross-country capacity (Figure 2).

![Figure 2. Explosion point with auger drill and compressed-air source PIC-3 on the basis of floating caterpillar transporter (works of JSC Yuzhmorgeologia in the North Caspian Sea) [4]](image)

Thus, considering the variety of geological tasks, the used technologies, as well as the difference in the energy and load capacity of vehicles used in different seismogeological conditions, it seems most relevant to develop technical means for excitation of elastic waves on the basis of the modular principle.
In due course, this approach was justified by A.V. Kalinin with regard to the development of an electric spark source for marine seismoacoustic survey [2, 3]. With regard to the development of group compressed-air sources, the modular principle of equipment implies the creation of such a set of technical means that with a minimum nomenclature variety of devices used would ensure the maximum variety of characteristics necessary to solve a wide range of tasks in different seismogeological conditions.

With modular design of the compressor station and the control system, this task is essentially reduced to the creation of several universal linear subgroups with different total volumes, high reliability and good acoustic characteristics on the basis of a number of similar radiators (Bolt, Sleeve Gun, G.Gun, Pulse, Baby or others). The volumes of radiator chambers in a linear subgroup, their number, base of grouping and depth of immersion are chosen so that at simultaneous operation of the group the first pressure peaks of signals of separate radiators are summarized inphase while repeated shocks (taking into account reflection from “water-air” surface) are developed in antiphase.

3. Calculation of synchronous non-uniform compressed-air groups

Monograph [1] describes different methods of synthesis of synchronous non-uniform compressed-air groups, which imply the generation of a sum signal with fluctuation suppression. One of the simplest methods is as follows.

A linear subgroup is created from several clusters, the distances between which are chosen so that their mutual acoustic influence is absent or minimal. The distance between adjacent radiators in each cluster is selected so that their air bubbles during exhaust merge into a single volume. The pulsation period of the signal emitted by the cluster is about the same as the single total volume radiator, but the amplitude characteristics are much better: the amplitude of the first peak of the sum cluster signal is significantly higher and almost equal to the sum of the amplitudes of the signals of individual radiators. The amplitude of the second peak (i.e. pulsation) is significantly lower than that of a single total volume radiator.

The volumes of working chambers of radiators (clusters) \( V_i \) are chosen so that all pulsations (second peaks) do not develop inphase, but form the sequence of impulses with approximately constant difference of pulsation periods by \( \Delta T \) (Figure 3, b). The \( \Delta T \) is chosen so that the reflection of repeated peak of \((i-1)\) signal from “water-air” surface coincided with repeated peak of \( i \) signal and ensured its quenching. At the same time \( \Delta T \) shall be equal to wave transit time from the radiator to “water-air” surface and back: \( \Delta T = 2h/c \), where \( h \) – depth of immersion of the radiator, \( c \) – speed of distribution of elastic waves in water \( c = 1500 \text{ m/s} \).

According to the known Rayleigh-Willis formula [1–3, 9, 10], at fixed operating pressure of compressed air and equal depth of radiation immersion, the pulsation periods of \( T_i \) signals and volumes of working chambers \( V_i \) are bound by the ratio:

\[
T_i = k V_i^{1/3},
\]

where \( k \) – coefficient depending on the radiator design; at the same time

\[
T_{i+1} = T_i + \Delta T.
\]

Substituting in (2) the expression (1) for the pulsation period \( T_i \), after small transformations we get a recurrent formula for calculating the volumes of working chambers of compressed-air radiators (clusters) in a linear subgroup:

\[
V_i = V_1[(1+2h(i-1))/(cT_1)]^3, \quad i = 2, ..., n
\]

where \( V_1 \) and \( T_1 \) – volume of the working chamber and the pulsation period of the signal of the 1st radiator of the linear subgroup having the minimum volume, \( n \) – number of clusters in the line. The final configuration setting can be performed after an experimental study of the acoustic characteristics of the group.

As an example, Figure 3 shows the calculation of configuration of a linear subgroup of 4 clusters (9 radiators) with the total volume of 10 dm\(^3\) located on the basis of 12 m.

The calculation of cluster signals, sum signal of linear group and its amplitude spectrum is performed in MathCAD on the basis of algorithms similar to those implemented in known Gundalf™ [10].
Figure 3. Calculation of Subarray linear subgroup configuration (N = 9, VΣ = 10 dm³, h = 5 m).

4. Implementation of interference systems with adjustable directional characteristic
The use of compressed-air groups with a large total volume is only possible on specialized geophysical vessels equipped with both complex lifting equipment necessary for round-trip operations and for towing large compressed-air groups, as well as improved and powerful compressor equipment and corresponding control systems.

However, the use of large non-uniform groups is justified because along with the formation of simple in shape and short in duration signals with a wideband spectrum, it is also possible to significantly increase the amplitude and energy of radiation and thereby significantly increase the noise immunity and depth of marine seismic surveys.
Another important circumstance is that large groups are generally located on a base that is commensurate with wavelength allowing such groups to be used as directional interference systems as well. At synchronous actuation such linear or spatial groups have directional characteristic with the maximum in vertical direction. By introducing time delays at the moments of actuation of adjacent radiators or adjacent subgroups, it is possible to implement an interference system with a controlled directional characteristic, which at the excitation stage will generate waves at predetermined apparent speeds.

Such an interference system can be created by simply combining identical linear subgroups into a corresponding areal system. Due to such association amplitude of a sum signal in the direction of an acoustic axis of the group increases approximately in proportion to the number of the united subgroups $K$, and the density of acoustic energy flow – in proportion to $K^2$. In addition to the change in amplitude and energy indices, there is a significant change in directional characteristics of the group.

As an example Figure 4, a and b shows the modules of the generalized interferential characteristics, respectively, in longitudinal (XOZ) and cross (YOZ) planes of linear subgroup Subarray-9/10 with the immersion depth of $h = 5 \, m$ calculated at $\alpha_0 = 0^\circ$ (synchronous operation), on Y axis – angle down. The configuration of the line group Subarray-9/10 is shown in Figure 3, a.

![Figure 4](image)

Figure 4. Modules of generalized characteristics of linear compressed-air group at $h = 5 \, m$

Figure 3, c shows that one such linear subgroup has good acoustic parameters: the calculated amplitude of $P-P$ signal is 32.7 bar·m, the degree of pulsation quenching $P/B – 16.7$, however, as Figure 4 shows, the group length of $D = 12 \, m$ is characterized by relatively low direction even in the longitudinal $XOZ$ plane ($\beta = 0^\circ$). In the cross $YOZ$ plane ($\beta = 90^\circ$) the direction of any one linear group corresponds to the direction of a point source.
To compress the directional characteristic of a group in the YOZ plane, a transverse grouping of lines is used, i.e. their combination into a single areal group. For example, Figure 4, c and d show the generalized characteristics in the YOZ plane of two areal groups consisting of two and four identical linear subgroups (Subarray-9/10, \( h = 5 \text{ m} \)), respectively, towed in parallel with the spacing between the lines \( \Delta Y = 6.0 \text{ m} \). From comparison of Figure 4, b, c and d we see that there is very effective cross compression of the directional characteristic of the spatial group. However, in the longitudinal plane \( \text{XOZ} \), the directional characteristics of all these variants of the groups still look as shown in Figure 4, a.

Clearly, in the longitudinal plane \( \text{XOZ} \), further compression of the main characteristic can also be achieved by increasing the longitudinal grouping base \( D \). Considering that the length of each line is structurally fixed and is determined by the length of the scaffold on the deck of a vessel, on which all linear subgroups in transport situation are placed, the longitudinal base of the group is most often increased only due to longitudinal span \( \Delta X \) between subgroups.

To illustrate the above, Figure 5 shows a series of \( \text{XOZ} \) plane characteristics and patterns calculated for one (a), two (b), and four subgroups (c) Subarray-9/10 at the depth of immersion \( h = 5 \text{ m} \), \( \alpha_0 = 0^\circ \) and the longitudinal span between subgroups \( \Delta X = 15 \text{ m} \), \( D \) – common base of the group. The angle of setting of all diagrams \( \alpha_0 = 0^\circ \) (synchronous operation of radiators).

Figure 5. Modules of generalized characteristics in \( \text{XOZ} \) plane and directional diagram at frequency \( f_0 = 75 \text{ Hz} \) of linear compressed-air group at \( h = 5 \text{ m} \)
Figure 6. Free-space diagrams of areal groups at $f_0=75$ Hz

Figure 5 shows that the main radiation lobe created in the vertical direction with the increase of span $\Delta X$ is considerably narrowed on axis $X$.

Figure 6 shows spatial directional patterns of three options of the areal groups calculated at a frequency of $f_0 = 75$ Hz for one (a), two (b) and four parallel subgroups (c) of Subarray-9/10 at the immersion depth of $h = 5$ m, $\alpha_0 = 0^\circ$ and the cross span between subgroups $\Delta Y = 6$ m.

Figure 6 shows that the main radiation lobe created in the vertical direction with the increase in the group base on $Y$ axis (from 0 to $3\Delta Y$) is also considerably narrowed on $Y$ axis.

Thus, choosing the corresponding longitudinal and cross spans between subgroups $\Delta X$ and $\Delta Y$, as well as setting a certain operation law of radiators for each subgroup via delays {$\Delta t_i$} it is possible to concentrate the emitted energy rather efficiently in any direction of the lower half-space within any set space angle.

However, the practice shows that the compression of the directional characteristic of the group in the longitudinal plane XOZ should be confined to certain limits. Thus, for subsequent processing of information according to CDP algorithms, it is desirable that target reflections on seismograms are maintained in shape and amplitude along the whole length of the hodograph. This allows maximizing the effect of the subsequent summation.

Figure 7 shows that for this purpose it is necessary that when grouping radiators the main radiation lobe is created in the $\alpha_0$ direction, and the width of this lobe on level 0.707 is determined by the angles $\alpha_{\min}$ and $\alpha_{\max}$ corresponding to the exit of seismic beams to final points $X_{\min}$ and $X_{\max}$ of the end-on receiver.

Figure 7. Choice of group radiation lobe width: $X_{\min}$ – offset of the receiving device; $X_{\max}$ – far end coordinate of the receiver; $X_{\max} = X_{\min} + L$; $L$ – length of the receiver; $X_{cp} = X_{\min} + L/2$ – streamer midpoint; $H$ – reflector depth
Depending on the length of the receiving device $L$ and the reflector depth $H$, the values $\alpha_0$, $\alpha_{\text{min}}$ and $\alpha_{\text{max}}$ as a first approximation can be presented by the following obvious expressions:

\[
\alpha_{\text{min}} = \arctg \left( \frac{X_{\text{min}}}{2H} \right);
\]
\[
\alpha_0 = \arctg \left( \frac{X_{\text{cp}}}{2H} \right);
\]
\[
\alpha_{\text{max}} = \arctg \left( \frac{X_{\text{max}}}{2H} \right).
\]

Figure 8 shows the dependences $\alpha_0(H)$, $\alpha_{\text{min}}(H)$ and $\alpha_{\text{max}}(H)$ calculated for receiving devices of different length and allowing estimating approximately the necessary width of the main reflection lobe of the compressed-air group in the longitudinal XOZ plane.

![Graphs showing dependences](image)

Figure 8. Dependences $\alpha_0(H)$, $\alpha_{\text{min}}(H)$ and $\alpha_{\text{max}}(H)$ calculated for receiving devices of different length

More precisely, taking into account the speeds of elastic waves in the environment and complex trajectories of beams, the values $\alpha_0$, $\alpha_{\text{min}}$ and $\alpha_{\text{max}}$ can be defined, for example, by the VOLNA-M software package for the modeling of seismic wave fields, which is specially developed for the correct solution of such tasks [5]. The modeling of beam diagrams shows that the interval of angles $\alpha_{\text{min}}$ – $\alpha_{\text{max}}$ restricting the limits of a beam tube in the longitudinal XOZ plane getting for receiving setting can significantly depend on high-speed differentiation of a section (Figure 9).

For example, the comparison of Figure 9, a and Figure 9, b shows that in order to study the borders under a high-speed layer, the energy radiated by a source shall be concentrated in narrower interval of angles $\alpha_{\text{min}}$ – $\alpha_{\text{max}}$ that will require the increase in the base of group D in the longitudinal XOZ plane.
Figure 9. Beam patterns of reflected waves obtained for two model sections with different speed $V_p$ in the ninth layer

5. Conclusion
This paper briefly discusses the basic principles of construction of group compressed-air sources for marine seismic survey. It is shown that the most important factors determining the choice of source parameters and specific research technology are the nature of geological tasks and seismogeological conditions, which primarily depend on the sea depth in the study area.

A simple method of calculating the configuration of linear subgroups with fluctuation suppression is described, as well as examples of building linear and spatial groups based on them with pronounced directional properties are considered. For more accurate and reasonable selection of seismic survey methods, including parameters of compressed-air sources grouping, it is recommended to use modern software tools for simulation of seismic wave fields and calculation of characteristics of any linear and spatial interference systems on the basis of pneumatic radiators.

References
[1] Gulenko V I 2003 Compressed-air sources of elastic waves for marine seismics Monograph (Krasnodar: KubSU) 313 p
[2] Kalinin A V, Azimi Sh A, Kalinin V V et al 1972 of immersion depth of pressure sparker source in seismoacoustic study in water areas In Applied geophysics iss. 65 (Moscow: Nedra) pp 84–95
[3] Kalinin A V, Kalinin V V and Pivovarov B L 1983 Seismoacoustic studies in water areas (Moscow: Nedra) 203 p
[4] Gulenko V I and Shumsky B V 2007 Marine seismic survey technology in shallow water limit and transit zone Monograph (Krasnodar: KubSU) 111 p
[5] Gontarenko I A 2012 Development of software tools for rapid simulation of seismic wave fields Georesources 1(43) 15–8
[6] Shumsky B V 2008 Technology of seismic studies of 2D MOV OGT in the limit shallow water and transit zones Cand. Dissertation (Krasnodar: KubSU) 28 p
[7] Samsonov E A 2012 Comparative characteristic of high-resolution seismic survey (HRS) and ultra-HRS during engineering surveying in water areas Proc. of the 39 session of the Int. Sci. Seminar named after Uspensky (Voronezh, 30 January – 02 February) 246 p
[8] Shallow seismic vessel NIS Seeker-5 Materials of JSC Sevmorneftegeophysics Retrieved from: http://www.smnggeophysics.com/i/iskatel5-rus.pdf
[9] Johnston R C, Reed D H and Desler J F 1988 Special report on the SEG Technical Standards Committee: SEG Standard specifying marine seismic energy sources Geophys. 53(4) 566–75
[10] Hatton L Gundalf™ – an airgun array modelling package Retrieved from: http://www.gundalf.com
[11] Hatton L 2008 The broadband acoustic output of marine seismic airgun sources Proceedings of the Institute of Acoustics, Underwater Noise (Southampton, England)