Principles of constructing control systems for group pneumatic sources for marine seismic exploration

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Abstract. To date, powerful pneumatic sources with dozens and sometimes with more than a hundred sources exhibit rather complex control systems with high functionality to ensure starting and automatic synchronization of sources, operation control, and current monitoring of group parameters and acoustic characteristics of the excited signals. The paper considers the basic principles of constructing control systems for group pneumatic sources and provides the requirements for the Astra-M system developed by Kuban State University in collaboration with JSC Yuzhmorgeologiya. The block diagram of the system and a number of its characteristics are presented. The paper discusses in detail the algorithm for automatic correction of the response times of group sources in the Astra-M system and presents the results of simulation and full-scale experiments.

1. Introduction
All over the world, a steady trend towards the use of more complex linear and areal radiating systems with dozens of pneumatic sources as part of the instrumental complex has been observed lately in offshore oil and gas seismic exploration. To date, such sources have already been installed on some domestic geophysical vessels.

Control of operation and parameters (monitoring) of these large and complex radiating systems becomes possible only with the use of a control computer that performs the entire extensive set of functions for control, starting and monitoring of the main technological parameters of the radiating system in a short period of time between explosions.

Currently used powerful pneumatic sources with dozens and sometimes with a hundred group sources exhibit rather complex controls with high functionality to provide starting and automatic synchronization of sources, operation control, and current monitoring of group parameters and acoustic characteristics of the excited signals.

The foreign control systems for pneumatic groups such as Aircon 1-81 and Aircon III controllers by Input/Output Inc. (USA), VZAD controller by Prakla-Seismos AG (Germany), Gunda system by GECO (Norway), LRS-100 system by Litton Resources Systems, Tiger II by Texas Instruments Inc., GCS90 controllers by Syntron Inc. (USA), and Big Shot by Real Time Systems Inc. (USA) have been widely used in recent years.

The domestic systems close to the best foreign models are programmable controllers Astra and Astra-M developed by Kuban State University in collaboration with JSC Yuzhmorgeologiya and manufactured in small series by NPO Neftegeofizpribor (Krasnodar).
The paper discusses the basic principles of construction and some characteristics of the multifunctional computerized control system for linear pneumatic group sources for marine seismic exploration Astra-M.

2. Basic requirements for control system for group pneumatic sources

The above characteristics of domestic and foreign systems analyzed with due regard to the main trends in development of radiating systems for marine seismic exploration make it possible to formulate the main requirements for the developed multifunctional control system of pneumatic groups Astra-M.

1. The system should ensure efficient operation of large pneumatic groups that comprise up to 50 sources with built-in trigger moment sensors (TMS), with a minimum time interval for response times of up to 6 s, with launching of all sources both synchronously and according to the specified algorithm with automatic correction of response times. The internal launch of the system should be carried out using the computer timer, and the external launch should be performed using the seismic station or the host computer of the seismic complex.

2. The system should provide continuous monitoring of the current state of the group with visualization at each explosion of all the main technological parameters that determine the effective source operation. The information displayed and the method of its presentation (in Russian and English) should provide clarity and ease of perception, as well as ensure the possibility for the operator to assess the work of both the entire group and individual sources with periodic and short-term observation of the monitor of the Astra-M system.

3. The system should provide for the possibility of independent parallel control of acoustic signals at least at 20 points in the near zone of the group sources, with the display on the monitor of all the recorded signals or any individual signal. In this case, the system should provide, if necessary, the calculation and visualization of the spectral characteristics of individual signals of subgroups (clusters), and the synthesis and visualization of the total signal and the amplitude spectrum of the entire group for the far zone.

4. The system should provide automatic control of the source operation (in Russian or English) with documentation during its operation on the profile of such basic technological parameters as the working air pressure in the subgroups, the depth of their immersion, and the assessment of standard deviations of the response times of all the group sources in a sliding window. After each explosion, the system should ensure the transfer of all these parameters to the host computer for subsequent recording in the label of each seismogram. In the main mode, the system should ensure the accumulation of statistics of faults of all the group sources in the profile.

5. In the testing mode, it is necessary to check all functional blocks of the controller, check the status and diagnose faults of the sources, measure response times, and check and calibrate the sensors.

6. The system should be simple, reliable and easy to use; in terms of its dimensions, weight and power consumption, the system must correspond to the capabilities of geophysical vessels, including low-tonnage vessels intended for work in shallow waters. During operation, the system should be maintained by the staff of shift operators, without the involvement of additional staff.

A block diagram of the Astra-M multifunctional control system for pneumatic sources, which meets all the above requirements, is presented in Figure 1.

The block diagram shows that the system contains five functional blocks, which ensures the operation of one subgroup of ten pneumatic sources equipped with TMS sensors, pressure and depth sensors (two per one subgroup), and a 20-channel acoustic unit with 20 connected hydrophones to monitor the acoustic radiation of the group in the near zone. The control computer is connected to the functional blocks and to the host computer using a special interface. The printer included in the system prints the report on the source group on the profile.

The software of the Astra-M system works in both the DOS and the WINDOWS environments and ensures the system operation in all modes with the performance of all the above functions.

The Astra-M system can ensure the operation of the group of any pneumatic sources with built-in TMS sensors and a response pulse amplitude from 60 to 260 V at a maximum current of an electro-
pneumatic valve (EPV) up to 10 A (for example, the Pulse type, etc.). In this case, the duration of the response pulse is about 20 ms, the range of measurement and correction of response times of the sources is 0–100 ms with a resolution of 0.01 ms.

3. Solving the problem of automatic synchronization of group pneumatic sources

The paper [1] presents the results of studying the stability characteristics of the response times of pneumatic sources of the Signal series. In recent years, similar studies have been carried out with sources of the Pulse series. These data indicate that in the first tens (or even hundreds) of the source responses, its own response time remains stable and obeys the normal distribution law with small standard deviations from the mathematical expectation of the order of 0.1–0.3 ms at the constant operating pressure and parameters of the response pulse supplied to the computer.

At the same time, longer observation of this process with operating time up to thousands of responses shows that due to slow variations in operating pressure, wear of O-rings, irregularities in the supply and removal of lubricant and a number of other possible reasons, there are slow fluctuations of the average (for several tens of successive measurements) of the source response time, with a deviation from the initial time up to 2–3 ms. With regard to the fact that synchronization of the group is usually carried out during the initial shooting of sources when entering the profile, and due to the above reasons the group can completely exit the synchronous response mode after several hours of operation, as a result of which the spectral and energy characteristics of the excited signals will be worse than expected [2].

Figure 2 shows an example of a sequential series of signals in the far zone of 8 sources of the Pulse-5 series recorded with an interval of about 30 min when operating without using the automatic correction.
Figure 2. Oscillograms of signals in the far zone of a group of eight Puls-5 pneumatic sources operating in the trigger mode without automatic correction: (a) signal immediately after correction, (b) signal recorded 30 minutes after correction, (c) signal recorded after 1 hour.

These records show that due to desynchronization of the sources the amplitude of the total signal of the group decreased more than two-fold after 1 hour of operation.

The complexity of maintenance the seismic equipment and the large amount of information controlled by the operator exclude the possibility of continuous monitoring of the group synchronicity and actions of the operator in order to correct the response times of the sources when operating on the profile. All this indicates the need to create and employ such systems for control of sources with automatic maintenance of the synchronous operation mode of the group.

The task of automatic synchronization of pneumatic sources in the group is set. The response time of the pneumatic source $T_{k}$ measured by the control system at the $n$-th explosion (the time from the moment the trigger pulse is applied to the valve until the moment the signal arrives from the trigger moment sensor at the beginning of the exhaust) can be represented as a sum of two independent components:
\[ T'_k = T_{k0} + R'_k, \]

where \( T_{k0} \) is the response time of the source (in the absence of disturbing factors, such as pressure variations, wear of O-rings, non-uniformity of supply and removal of lubricant, etc.), which is a stationary random discrete function with a normal distribution law, mathematical expectation \( T_c \) and standard deviation \( \sigma \) of the order of 0.1–0.3 ms;

\( R'_k \) is the component of the source response time that fluctuates under the impact of the above perturbing factors, relatively slowly changes, in the general case, a nonstationary discrete random function (it can be a deterministic function).

In terms of the theory of automatic control [4, 5, 6], the task of creating a control system with automatic synchronization of a group of \( M \) sources is reduced to the construction of the \( k \)-channel discrete prediction filter that suppresses \( R'_k \) components for each source of the group. In the general case, the response times of each source can be considered independent of the response times of other sources of the group [7, 8, 9], it is sufficient to construct a prediction filter for one channel, and the filters for other channels of the control system can be constructed similarly.

The requirements imposed on the prediction filter are as follows.

1. The input parameters of the discrete prediction filter algorithm are the measured values of the corrected response times of the sources (including the previous values), and the specified response time of the group \( T_0 \). There is no a priori information about the form of the function that describes the fluctuation of \( R'_k \) (except for the information that this function changes in time relatively slowly).

2. The algorithm of the discrete prediction filter should be stable for a wide range of functions that describe fluctuations and provide high-quality suppression of slow fluctuations in the source response time (no less than 8–10 fold). The noise introduced by the operator in the absence of fluctuations should not increase the root-mean-square deviations of the response times of the sources more than 1–2-fold. The criterion for the quality of the fluctuation suppression can be the criterion of the minimum of the sum of the standard deviations of the corrected (measured) response times of the sources \( T_k \) from the given time \( T_0 \) during \( N \) cycles:

\[ E = \min \sqrt{\frac{\sum_{k=1}^{N}(T_k-T_0)^2}{N}}. \]

3. The algorithm of the discrete prediction filter should be simple and, in the \( k \)-channel version, software implemented within the computer capabilities, which is part of the control system.

A number of simple and obvious algorithms used in the first foreign control systems were studied using the simulation method. The study showed that at \( \sigma \geq 0.3 \) ms and in the absence of fluctuations these filters become unstable and can introduce significant noise, that is, ‘swinging’ of the source response times, which impairs the synchronization quality indicator 5–6 fold. A similar effect can be observed in the presence of fluctuations. These algorithms work somewhat better at values of \( \sigma = 0.1–0.3 \) ms, however, they do not satisfy the above requirements [3, 10, 11].

The best results were obtained for the algorithm of the prediction discrete filter with automatic correction, which contains the integral and differential components that consider changes in the source response time deviations over the last \( L \) cycles taken with the appropriate weight coefficients. In this algorithm, the correction value \( Q_{k+1} \) of the time of the \((k+1)\)-th response of the source is calculated by equation [3]:

\[ Q_{k+1} = \frac{\sum_{i=1}^{L}(\Delta k+1-i)q_i)+C\sum_{i=1}^{L}(\Delta k+1-l^\circ-i)Lq_i}{\sum_{i=1}^{L}q_i}, \]

where \( \Delta_k = Q_k + \Delta T_k = T_k - T_0 \);
\( \Delta T_k = T_k - T_0 \) is measured deviation of the \( k \)-th corrected response time from the given \( T_0 \);
\( q_i = 1 - \frac{i-1}{L} \) are weight coefficients of the law of forgetting;
\( i = 1, 2, ..., L \);
\( k = 1, 2, ..., N \) is sequential number of source triggering;
$C$ is proportionality factor for the differential component selected according to the criterion (2): $C \approx 2$.

The algorithm is shown in Figure 3, where the upper trace corresponds to the response times of the source without correction $T^*_k$, the lower trace corresponds to the corrected (measured) times $T_k$, and each calculation stage employ only $L$ values of $\Delta_k = Q_k + \Delta T_k$.

**Figure 3. Algorithm of the discrete prediction filter**

The efficiency of suppression of slowly changing fluctuations using the above algorithm is shown in Figure 4 (a–c). In addition to $T_k$ and $T^*_k$ values (indicated as $T_{1k}$) obtained using simulation in the MathCad 14 environment at $\sigma=0.1$ ms, $\sigma=0.2$ ms and $\sigma=0.3$ ms, indicators of the correction quality $E_1$ and $E_2$ calculated by substituting the corresponding values $T^*_k$ and $T_k$ into (2) are given.

The presented data show that the algorithm is stable, the degree of fluctuation suppression is at least 10, and the standard deviation of the response times of the sources with no fluctuations due to the noise introduced by the filter increases by no more than 10–20%.

Worse results were observed for fluctuations represented by discontinuous functions in the form of a single burst of response time, in the form of a step function that corresponds to a spontaneous transition of the source to a different response time, and in the form of a sawtooth function. The simulation results show that the considered filter skips only high-frequency components of fluctuations, while low-frequency components of discontinuous fluctuations are suppressed effectively.

Figure 5 shows the experimental dependences of the times of 200 responses of the Pulse-5 pneumatic source on the cycle number obtained during operation without automatic correction (a) and with automatic correction (b), as well as the corresponding histograms.

These data show that despite the fact that the automatic correction algorithm introduces insignificant additional noise, it provides effective suppression of fluctuations, which leads to a significant decrease in the range of the source response times.
4. Conclusion
The paper considers some principles of constructing control systems for group pneumatic sources and provides the basic requirements for the Astra-M system developed by Kuban State University in collaboration with JSC Yuzhmorgeologiya. The block diagram of the system and a number of its characteristics are presented.
The paper discusses the algorithm for automatic correction of the response times of group sources in the Astra-M system – a discrete prediction filter that ensures effective maintenance of both the synchronous operation mode of the group and any of the ten specified time laws. The results of simulation and full-scale experiments show that the properties of the developed discrete filter satisfy the requirements for automatic correction devices, and it can be successfully implemented by the control computer in the -channel version (M≤100) with the width of the sliding window L≈10.

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