On the development of the emitter assembly of an acoustic downhole device

Alfiya Gilmanova[1*], *Oleg* Filimonov[1], *Irida* Galiullina[1], *Eduard* Mukhamadeev[1], and *Elena* Guseinova[1]

[1]Institute of Oil and Gas FSBEI of HE "Ufa State Petroleum Technological University", (Branch in the City of Oktyabrsky), 54a, Devonskaya Street, Oktyabrsky, Republic of Bashkortostan, 452607, Russia

Abstract. The article considers narrow-band and broadband variants of the acoustic logging method, shows the advantages and disadvantages of existing radiators, describes the requirements for acoustic radiators of borehole devices for a wide frequency range from 0.5 to 40 kHz, shows the experimental and theoretical justification of the designs of radiator assemblies and the basic requirements for calculations. The result of the work is an upgraded design of the radiator assembly, which ensures the operation of broadband acoustic logging devices, described in detail in this article.

1 Introduction

One of the promising and universal methods for assessing the technical condition of cased and unsettled wells is the broadband acoustic logging (AK) method. The stability and quality of measurements of this method is ensured using technically sophisticated acoustic equipment with appropriate methodological, software and metrological support.It is known [2] that the acoustic method of well exploration imposes exceptionally high requirements on the design of acoustic probes, applied schemes for measuring acoustic parameters of rocks and near-well space, including the casing and cement ring. Moreover, depending on the conditions of use, the degree of complexity of the tasks to be solved and the requirements for the accuracy and reliability of the data obtained, these requirements can vary widely.

If at the first stages of the development of the AK method (narrow-band version) The task was to reliably register the amplitude-wave parameters of one type of elastic waves excited in the well, belonging to the longitudinal type of vibrations, then at the present stage of development of this method AK-Sh (broadband version) we are talking about registering the amplitude-time parameters of several types of elastic waves, differing in the mechanism of excitation and propagation in the well.These are, first of all, refracted, exchange and head longitudinal, transverse and reflected waves (P, S, PPP, PSP, etc.), as well as surface (L, L-St, St) and hydrowaves [3]. All these types of vibrations carry a huge amount of useful information about the environment, the accuracy and reliability of which depend on

---

* Corresponding author: alfiya_okt@mail.ru

the degree of optimality of their excitation and reception, which is not always possible to ensure due to significant and, sometimes, mutually exclusive requirements for the conditions of their implementation.

The main functional units of an acoustic downhole device are [1]:

- Emitters designed to excite vibrations in the environment.
- Receivers used to receive elastic waves.
- Acoustic insulators necessary to suppress the energy of elastic waves propagating in whole or in part through the body of the deep device.
- Centralizers necessary to hold the borehole probe on the axis of the well.
- Electronic, electrical components and circuits designed for synchronization, generation, amplification, registration and primary processing of signals coming from the surrounding space of the well.

In the article "Taking into account the influence of various factors on the accuracy of measurements when creating geophysical acoustic logging equipment" [1], the factors affecting the measurement error by borehole instruments of acoustic logging methods were considered in detail and the systematic components of these errors were analyzed: the quality of design, manufacture of equipment and its proper operation. In this article, we will consider the following of the factors specified in [1] – the node of the acoustic radiator.

2 Methods and Materials

The results obtained, briefly presented in the article, are based on the analysis of theoretical data, calculations, experimental data and borehole studies. Acoustic emitters of downhole devices should provide for operation within a wide frequency range from 0.5 to 40 kHz [4]. This will allow you to vary the very important quality of the devices - the sensitivity of the receivers over a wide range in both cased and unsettled wells. However, this circumstance entails special requirements for both emitters and receivers (receiving-emitting converters), which must ensure effective generation and reception of elastic waves in such a wide range.

Acoustic radiators, including the design of their assemblies, must meet the following requirements [2, 5]:

- Must ensure the emission of elastic waves into an aggressive environment with high wave resistance relative to air (mineralized water, washing liquid or oil).
- The radiator must be operable at hydrostatic pressures up to 1000 kGf/cm2 and temperatures up to 150 ° C with a constant electroacoustic efficiency of the maximum value.
- The outer diameter of the radiator is limited by GOST for downhole equipment and the requirement for the diameter of downhole equipment designed to work in small diameter wells.
- The radiator must be as resistant to mechanical shocks as possible.
- The emitter must have high long-term stability, i.e. a small spread in the dynamic characteristics of the excited pulse in a homogeneous medium over time.
- The power consumed by the emitter should not exceed 200 watts, since it is limited by the bandwidth of the cable (the repetition rate should be at least 6 Hz based on the logging speed).
- The emitter must excite the most powerful short acoustic pulse with the main energy in the prevailing frequency range.

3 Results and Discussion

There are many different types of emitters used to excite ultrasonic vibrations in a liquid: thermal, spark, electrodynamic, pneumatic, hydrodynamic, magnetostrictive, piezoelectric, etc. Magnetostrictive radiators have become the most widely used in both foreign and domestic AK equipment [6, 7].

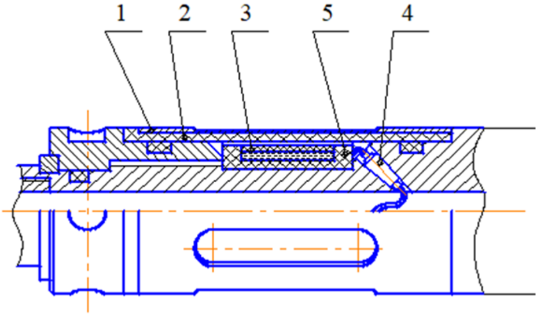
The main advantages of magnetostrictive emitters are low sensitivity to the external environment, simplicity of exciting devices, high stability of the elastic pulse with repeated repetition of radiation, the possibility of manufacturing emitters of various shapes. Nickel, permendure and magnetostrictive ferrites are usually used for the manufacture of magnetostrictive radiators.

The disadvantage of such emitters is the dependence of their ferromagnetic properties on the heat treatment regime of the material [4].

The appearance of modern piezoelectric converters with improved frequency and energy characteristics made it possible to use them not only as receivers, but also as emitters of elastic waves, of course, while providing the necessary broadband.

Based on experimental studies and calculations, it was revealed that the broadband of the emitter node is provided by the following features of its design (Figure.1):

- Casing (1), acoustically transparent in any direction.
- External pressure compensator (2).
- By making the ends of the assembly adjacent to the converter with a bevel at an angle greater than the second critical angle.
- A high coefficient of use of the diameter of the radiator, for which its outer surface is located close to the inner surface of the compensator
- The original design of the damping device.



1 – casing; 2 – compensator; 3 – radiator; 4 – electric leads; 5 – damper

Fig. 1. The node of the acoustic radiator.

Of course, the receiving converters, in turn, have certain requirements according to the principles of construction [4, 8, 9]. Within the framework of this article, converters are considered from the point of view of the emitter, therefore acoustic receivers are mentioned in passing.

Based on the conditions of use, the transducers were tested for temperature stability. The results show [4] that an increase in temperature at constant pressure decreases the signal, and an increase in pressure at constant temperature increases the signal. This leads to the fact that the change in the recorded amplitudes with a simultaneous increase in temperature and pressure will be determined by the ratio of the rates of their increase. Assuming that the increase in pressure and temperature in real borehole conditions is close to experimental conditions, it can be assumed that the amplitude of the first entry will not change by more than 10-20%, and the second entry by 30%. For recording the time parameters and attenuation coefficients, such changes in the amplitudes of the recorded signals along the depth of the well do not play a significant role.

Given the practically stable behavior of the signal, i.e., a decrease with temperature changes and an increase with pressure increases, the use of amplitude parameters to isolate fractured cavernous zones against a background of homogeneous undisturbed rocks will be no less effective than under normal, stable conditions.

Tests of piezoceramic spheres of CTS-19 at negative and positive temperatures [5-14] showed the following:

- With a decrease in temperature to minus 45 ° C, the signal amplitude increased in kerosene by 34%, and in organosilicon liquid PMS-130A by only 28%, and the density of both increased by 7%. This is due to the increased viscosity of the organosilicon liquid, which means that the increased attenuation of the acoustic signal in the organosilicon liquid. (For reference: the speed of sound in kerosene v=1282 m/s, temperature coefficient b=-3.8 m/c/oS; in organosilicon liquid: v=980 m/s, b=-10.4 m/s/oS).
- When the temperature rises to 250 ° C in transformer oil, the amplitude decreased to 0.16-0.2 of the original. The density of transformer oil is reduced to 740 kg/m3, which is 0.83 of the density value under normal conditions. However, the propagation time of the acoustic signal, measured in a high-pressure chamber, deviates from a linear dependence in the direction of increase. This fact indicates that with an increase in temperature, despite an internal pressure of 5 MPa, the content of gas vapors in transformer oil increases, leading to an additional decrease in its density [15-17].

With an increase in temperature to 200 ° C and pressure to 150 MPa, the amplitude also decreases, although less, to the level of 0.8, since the additional pressure somewhat compensates for the decrease in density from temperature. Thermal stabilization of piezoceramic elements was achieved by cyclic training.

Studies [10] show that the wavelength of the equipment at a frequency of 25 kHz in steel pipes and cement ranges from 21 to 14 cm, which is many times greater than the total thickness of the column (1.0 cm) and the cement ring (2.5-3.5 cm). At high frequencies, the attenuation increases greatly. Therefore, the use of lower frequency converters in the equipment can increase the accuracy of the recorded parameters.

The need to ensure the stability of the amplitude-frequency characteristics of the receiving-emitting elements of the downhole device, as well as their relatively low mechanical strength, required the use of protective oil-filled containers with elastic walls made of oil-resistant rubber, which simultaneously serve as pressure compensators. The requirements for pressure compensators, based on the conditions of use of downhole AK devices, are as follows:

- The compensator must ensure minimal impact on the acoustic signal passing through it.
- The compensator must ensure a wide range of changes in the volume of the cavity (at t = 200^{o}C, the volume increases by 20%).
- The compensator must ensure reliable separation of the cavity from the borehole fluid during multiple cycles of external pressure changes.
- The compensator must operate in conditions of aggressive borehole fluid.

Experimental studies have shown that the compensator in the form of an oil- and gasoline-resistant 1.5 mm thick rubber sleeve protected by a thin-walled metal casing with special windows meets these requirements most fully. The experimental results shown in Table1 confirm the calculated data on the minimal effect on signal transmission of the wall of a metal casing with a thickness of no more than 1 mm [4].

Table 1. The effect of the casing wall thickness (mm) on the attenuation of the longitudinal wave amplitude.

Number of half-periods	**An open radiator**	**Steel**		**Stainless steel**		**Aluminum**		**Brass**
		2.0	1.0	2.5	1.0	1.8	1.5	0.5
1	7	6	7	5	7	7	7	7
2	14	9	13	8	14	11	12	13
3	31	20	29	15	30	27	29	28

For an aggressive environment, instead of a rubber compensator, the use of fluoroplastic with constant dimensions of protective metal casings is provided. Moreover, due to the fact that the fluoroplast has a high coefficient of thermal expansion (at t = 200°C, the diameter of 55 mm increases by 1.5 mm), fluoroplast expansion joints are equipped with additional end sealing elements [1].

The taper angle of the parts forming the cavity of the transducers and the size of the windows of the protective covers ensure free output and approach of the head ultrasonic wave at all possible values of the critical angle.

To increase the resolution by wave types, a piezoceramic element in the form of a cylinder is mounted on a sleeve made of a material that differs by an order of magnitude in terms of acoustic stiffness from the dielectric liquid filling the cavity of the receiving unit, and in such a way that there is practically no gap between the outer surface of the element and the inner surface of the compensator, and between the inner surface of the element and the outer surface of the sleeve, it is selected from the ratio between the maximum total increment of the transverse dimensions of the element and the sleeve and one sixteenth of the wavelength of elastic vibrations in a dielectric liquid at the upper frequency of the operating frequency range in mm (acoustic stiffness of the sleeve made of steel 35 x106 kG/m^{2}s; organosilicon liquid 1.5 x 106 kG/m^{2}s).

In order to exclude conditions for the excitation of vibrations in the internal volume of the piezoceramic element and resonant phenomena that negatively affect the frequency response of the converter and cause an increase in the time of transients after each elastic pulse, the sleeve under the piezoceramic element is hollow.

The maximum total increment of the transverse dimensions of the piezoceramic element and the sleeve resulting from their thermal expansion, determined for the operating temperature range at the upper frequency of the operating frequency range and ranging from 0.5 to 1 mm depending on the diameter of the transducers, as well as the use of a special rubber sleeve providing for the fit of the element with the selected gap, exclude the appearance of mechanical contact between the bushing and the receiving element. Such contact leads, as a rule, to instability of the conversion coefficient due to the phenomenon of the attached mass effect, depending on the degree of compression and the magnitude of the contact, caused primarily by the influence of temperature in the well. With the selected gap provided by the special design of the elastic sleeve, the phase lag does not exceed $\pi/4$ and the signal distortion does not worsen the measurement conditions.

The problem with the leads on the connecting wires running from the emitter node to the electronics unit [5, 10] is solved as follows: the wires from the piezoelectric receiver passing by the emitter are twisted bifilarly and placed in the screen, and a differential amplifier is used as the first stage of the downhole device amplifier - it amplifies the multipolar signal coming from the plates of the piezoceramic receiver In this case, various interference induced on wires and having the same polarity are mutually destroyed. Tests have shown that such a node design is less sensitive to mechanical impacts on the body of the electronics unit, and noise at the receiver during measurements is more stable [5].

4 Conclusion

Based on theoretical and experimental studies carried out taking into account the formulated principles and requirements, original technical solutions for the designs of acoustic radiator assemblies with high noise immunity and sensitivity in a wide frequency range (0.5-40 kHz) designed to work in a conventional and aggressive environment have been found, constructive ways to reduce the systematic and random components of measurement error have been proposed which made it possible to improve the quality and informativeness of the obtained borehole material.

The author expresses gratitude to the employees of JSC NPP VNIIGIS Agapitov V.V., Gutorov Yu.A., Mayorov V.P., Tkacheva N.I., Shariyazdanov Sh.Sh.Haidarov G.N. and others, together with whom a friendly team carried out work on the creation of acoustic devices for serial production.

References

1. A.M. Gilmanova, Consideration of various factors influencing acoustic logging equipment production accuracy, IOP Conference Series: Materials Science and Engineering, **560(1),** 012063 (2019)
2. A.M. Gilmanova, Metrological support of geophysical equipment for acoustic logging, IOP Conference Series: Earth and Environmental Science, **378(1),** 012080 (2019)
3. A.M. Gilmanova, Centralizing devices to complement acoustic logging tools, Journal of Physics Conference Series, **1753(1),** 012072 (2021)
4. A.M. Gilmanova, Computer-aided design systems for product life cycle stages, Journal of Physics Conference Series, **1661(1),** 012205 (2020)
5. E. Z. Mukhamadeev, Kh. N. Yagafarova, Frequency converter power reduction for controlling the hydraulic parameters of the pumping station, IOP Conference Series: Materials Science and Engineering, **560(1),** 012077 (2019)
6. S.A.Batalov, V.E.Andreev, V.M.Lobankov, V.Sh.Mukhametshin, Numerical simulation of the oil reservoir with regulated disturbances. Oil recovery stability simulation, Journal of Physics: Conference Series, **1333(3),** 032007 (2019)
7. A.S. Galeev, R.N. Suleymanov, O.V. Filimonov, Development of a laser beam to the line in measuring systems, IOP Conference Series: Materials Science and Engineering. **560(1),** 012125 (2019)
8. Kh.N. Yagafarova, I.G. Arslanov, R.A. Teregulov, Performance analysis of surface reducing gear of rod driven screw pump with involute gearing and Novikov gearing, Advances in Engineering Research (AER), **157,** 627-630 (2018)
9. M.S. Mullakaev, V.O. Abramov, A.A. Pechkov, Ultrasonic unit for restoring oil wells, Chemical and Petroleum Engineering, **45(3-4),** 133-137 (2009)
10. Yu. V. Shulgina, et al., The increase of ultrasound measurements accuracy with the use of two-frequency sounding, IOP Conference Series: Materials Science and Engineering, **81(1)** (2015)
11. A. I. Soldatov, et al., Measurement error reducing in the ultrasound time-pulse systems, IOP Conference Series: Materials Science and Engineering. **81(1)** (2015)
12. E. Crew Merle, Multipit a method for calibration of logging system, Trans, SPWLA 20 Annu. Logg. Symp., Tulsa, Okla, 1-15 (1979)

13. C.D. Shulby, M.D. Ferreira, R.F. de Mello, S.M. Aluisio, Theoretical learning guarantees applied to acoustic modelling, Journal of the Brazilian Computer Society, **25(1)** (2019)
14. Z.C. He, X.Y. Lin, E. Li, A non-contact acoustic pressure-based method for load identification in acoustic-structural interaction system with non-probabilistic uncertainty, Applied Acoustics, **148,** 223-237 (2019)
15. W.J.C. Verhagen, P. Bermell-Garcia, R.E.C. Van Dijk, R. Curran, A critical review of knowledge-based engineering: an identification of research challenges, Adv. Eng. Inform., **26(1),** 5-15 (2012)
16. S. Khodaygan, M.R. Movahhedy, Tolerance analysis of assemblies with asymmetric tolerances by unified uncertaintyaccumulation model based on fuzzy logic, Int. J. Adv. Manuf. Technol, **53(5–8),** 777–788 (2011)
17. B.J. David, G.J. James, C.J. Keith, H.J. Jenny, Y.J. Bob, C.J. Sean, An engineering design knowledge reuse methodology using process modelling, Res Eng Design, **18,** 37–48 (2007)