Centralizing devices to complement acoustic logging tools

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Abstract. One of the cornerstones to high-precision acoustic logging equipment is high reliability and maneuverability of tools in a sophisticated well. The paper outlines the requirements for centralizing devices (CD), experimental and theoretical rationale for different configurations, and the need for appropriate calculations. The outputs involve a series of updated centralizing devices, the classification of centralizing devices and a crossplot that all allow for an optimal centralizing configuration to be selected depending on the equipment available and a well examined.

1. Introduction

The factors affecting measurement errors in borehole acoustic logging tools showed [1] that the value of systematic contributing uncertainty depends on the quality of tool designs, manufacturing of the equipment and its proper maintenance. This uncertainty is also affected by a number of other unmanageable factors including sonde alignment, irregularity of radiation patterns, mismatch in spectral characteristics of transducers, discrepancy between the power parameters of emitters and the sensitivity of receivers, as well as non-compliance with the geometric dimensions of sondes during manufacturing [2, 3].

The paper addresses one of the most important principles – ensuring the alignment and maneuverability of devices in the wells explored with the following requirements for centralizing devices, namely:

- ensure that borehole-geophysical tools are aligned in the boreholes with a range of inside diameters from 50 to 250 mm;
- ensure that the device is axially centered while it travels in the wells with an angle of incidence of up to 90 °, i.e. vertical (VW), deviated (DW) and horizontal (GW) wells;
- to ensure that the devices are continuously travelling both through the cased boreholes, regardless of the nuisances to occur on a surface wall due to union joints, perforations, corrosion and deposits of salts, hydrates and paraffins, and through the open boreholes with fractures, cavities, trenches, protrusions, etc.

Strict and contradictory requirements are imposed to centralizers to acquire accurate, comprehensive and reliable information about the parameters and status of the wells to ensure repeatability of acoustic measurements. On the one hand, they should provide the arms to be rigidly and uniformly pressed to the borehole walls for a guaranteed stable sonde position relative to the axis of the well, and, on the other hand, they should provide the adequate maneuverability of devices.
travelling in the wells under a wide variety of geological and technical conditions to minimize the level of mechanical acoustic noise.

2. Methods and material
The results are based on the analysis of literature data, experimental and analytical methods.

3. Research and efficiency assessment
3.1. To ensure tool stability to the well axis, a centralizer design should address the frequency of transducers used in acoustic devices: for refracted waves, noise logging, reflected waves.

3.1.1. Acoustic logging (AL) tools feature circular transducers. High-resolution imaging depends on the location of the instrument relative to the axis in the well. A wave pattern received by the receiver is viewed as a wave train to arrive at the receiver from all sections of the borehole wall in the transverse plane of the receiver, including from diametrically opposite sections (Fig. 1). Given that the receiver is axially symmetric, the direction of all rays coincides with the receiver radii drawn to the sensing point. The wave energy transmitted to the receiver is maximum in this position. When the receiver is off-centered, the angles of incidence of some rays gradually increase (the energy transmitted by these rays decreases), while other rays do not touch the receiver at all. Thus, wave interference occurs, thereby causing the deformation of the wave pattern. As a result, the log data are distorted when recording AL time and amplitude parameters.

![Figure 1. Schematic for wave arrival at the receiver: I – axially symmetric position of the transducer; II – biased position of the receiver relative to the axis of the well](image)

A permissible deflection of the transducers from the borehole is determined by the I.S. Berzon’s formula [2]

\[
\Delta r \leq \frac{V_l}{16f} \text{ (mm),}
\]

where \( V_l \) is the velocity of the elastic wave in the liquid; \( f \) is the frequency of the recorded signal, Hz.

For the frequencies of 22, 20, 18, 12 kHz used in AL tools, the permissible displacements will be 4.6; 5; 5.6; 8.3 mm, respectively, which means that with a decrease in the emitter frequency, the permissible value of the transducer displacement from the well axis increases, therefore, for small-sized AL tools with a maximum radiation frequency of 25-30 kHz, the optimal receiver displacement from the well axis should be less than 4.5 mm.

The relationship between the waveform amplitude and the displacement of the transducers and the sonde itself in deviated and horizontal wells was calculated by defining the maximum theoretical amplitude as the amplitude of the compressional wave at a distance from the borehole axis equal to the receiver radius \( r = 12 \text{mm} \) used in the experiment. The output data were compared with the test values shown in Table 1.

Changing amplitudes of various semi-periods were also evaluated both for the case when the receiver alone is biased and for the case when the entire sonde is biased. It was found that the slowness of the first wave arrival is much faster when the sonde is displaced in its entirety in the vertical and
horizontal wells rather than when the receiver alone is biased (or only the emitter). All the data obtained made it possible to accept that a permissible sonde standoff in the borehole at a transmitter frequency of 25-30 kHz should also not exceed 4-5 mm.

Table 1. The amplitude of elastic waveforms at various displacements of the transducers from the borehole

| Displacements of the transducers from the borehole | 0 | 2 | 4 | 6 | 8 | 12 |
|---------------------------------------------------|---|---|---|---|---|----|
| Signal amplitude (relative units)                 | 1.0 | 0.87 | 0.65 | 0.49 | 0.41 | 0.35 |
| Test amplitude                                   | 1.0 | 0.91 | 0.83 | 0.79 | 0.74 | 0.67 |
| Theoretical amplitude                            | 1.0 | 0.91 | 0.83 | 0.79 | 0.74 | 0.67 |

3.1.2. In spectral noise logging (SNL) tools, the frequency range is used by an order of magnitude smaller than in AL tools, i.e. sound sondes are almost insensitive to misalignments, which means that centralizers developed for AL tools fully satisfy the requirements for noise logging tools.

3.1.3. Sonic video logging (SVL) tools operate with high-frequency converters from 600 to 1500 kHz, which means that even more stringent requirements are imposed on their centralizers than those in AL tools. This is due to the principal criterion [4]:

\[ \Delta r \leq \frac{\lambda}{16}, \]  

where \( \Delta r \) is the transducer standoff; \( \lambda \) is the wave length.

The length of elastic waves in this case varies from 1.9 to 1.0 mm with the standoff to be theoretically from 0.95 mm to 0.5 mm! In practice, it is impossible to achieve this merely through construction solutions (centralizers based on speculative conclusions showed that pressure slide blocks, due to the arms being excessively rigidly pressed to the borehole walls, leave behind traces on the casing walls). Along with a gentle construction solution, software and metrological methods were found to assist in reducing certain measurement errors [3].

3.2. To minimize the level of mechanical acoustic noise, it is necessary to ensure adequate maneuverability of devices in boreholes under a wide variety of geological and technical conditions. To improve maneuverability, elongate members (upwardly extending arms or levers) should be made of a material that has a low friction factor, e.g., brass, bronze, steel, nylon, fluoroplastic, etc. It should be significantly lower than that of rubber because rubber is an elastic, pliable material that, once subject to irregularities, increases the friction factor. Steel, on the contrary, is a hard, rigid material that is resistant to irregularities. Therefore, with a fairly smooth friction surface, its friction factor does not depend on the nature of rock roughness [4].

It should be borne in mind that all kinds of noise, including those induced by the arm-wall frictions, have an enormous effect on the quality of borehole data acquired through acoustic logging, and especially noise logging (except for sonic video logging). This is the case when rubber, being able to absorb vibration, waves and noises due to intermolecular friction, is dispensable for reinforcing the elements exposed to stresses and vibrations when they follow rough surface. Rubber eliminates a bad effect of these factors on the measurement procedure. Eventually, sliding friction was decided to replace rotary friction resulting in the use of rotating rubber or polyurethane slide blocks in the centralizers [5].

3.3. Existing centralizer designs for acoustic logging can virtually be divided into three groups: rod (rubber), lantern-type and levered.

The tests revealed that the most high-quality and stable recording of amplitude parameters in the open wells is provided by lantern-type centralizers comprising 4 to 6 upwardly extending arms (Fig. 2). Here a critically large difference between the accelerated forces to occur at the maximum and minimum opening moments was reduced through interchangeable arms that have the respective pre-deformation determined by the formula:

\[ f_0 = \Delta H \frac{R_{\text{max}} \cdot \Delta^3}{R_{\text{min}} \cdot l_0^3} - 1, \]  

(3)
where $\Delta H$ is the operating deformation; $R_{\text{max}}$ is the force at the end of the operating deformation ($f_0 + \Delta H$); $R_{\text{min}}$ is the force of the pre-deformed bow spring; $l_o$ is the spacing between the ends of the pre-deformed bow spring; $l$ is the spacing between the ends of the maximum deformed bow spring.

With this approach, the spring force throughout the opening range from 178 to 250 mm and from 50 to 152 mm changes to the required value 1.7 times ($R_{\text{max}}/R_{\text{min}}=1.7$). One standard bow spring size was decided to produce for operations in the boreholes with diameters from 50 to 152 mm, with a combined force applied by each centralizer to be from 14.8 to 8.7 kg. The second size was for the boreholes with diameters from 178 to 250 mm, with a combined force applied by each centralizer to be from 8.7 to 5.1 kg.

To calculate the residual stresses arising during the manufacture of flexion springs, they should be analyzed for bending at a reduced permissible voltage. Moreover, to prevent the springs from breaking at the points they are the most poorly coupled with wireline wipers, it is necessary to determine the maximum contact stress using a computation technique applicable for the cases when convex surface is in contact with a plane [6].

Based on the findings, a crossplot was developed to select the size and number of elongate arms, depending on the purpose of the device, design and type of boreholes (Fig. 5). Levered centralizers (Fig. 3) are the most reliable and durable tools for operations in cased wells. The design provides a favorable combination of centering rigidity and relatively soft passing through the borehole. The study resulted in the following disadvantages to be eliminated:

- the inefficiency of these centralizers in small diameter wells was addressed by mounting spring-loaded steel clips on the arms and employing elongate members in the form of plate or disk springs. Helical compression springs with theoretically calculated and experimentally confirmed elastic characteristics were selected as elongate members. The characteristics encompass the weight of the device, the maximum opening moment provided by the arms, etc. It was shown experimentally that it is necessary to place springs that have identical strengths not on one but on both sides of the centralizer to ensure reliable up and down operations in telescoping and custom casings;

- the level of noise signals induced by the arm-wall frictions was reduced through the use of lever centralizing devices designed to include unequal arms and a pair of shock absorbing rollers mounted onto the joint assembly (by the way, the arms in the lantern-type centralizers were also equipped with a pair of rubberized rollers in axial moving relationship with the arms [5]).
the device is axially aligned to the eccentric well (in open boreholes having local misaligned changes in the form of cavities and protrusions, as well as in corroded casing strings) by the centralizing device shown in Fig. 6. Its arms can independently move about the pivot [5].

- Selecting the size and number of elongate arms depending on the weight of the device, operating frequency, angle of incidence and type of well.

Analytic graphs of centralizer resistance force versus the angle of incidence of a well

S1 – by weight of collar locator CBL-CW-48
S2 – by weight of CBL-CW-48
S3 – by weight of CBL-CW-36

Graphs of contact stresses produced by elongate arms versus the size of contact areas, angle of incidence and type of well

Service string – R1 arm
Service string – R2 arm
Crystalline rocks – R1 arm
Crystalline rocks – R2 arm
Sedimentary rocks – R1 arm
Sedimentary rocks – R2 arm

Figure 5. Cross-plot of the size versus the number of elongate arms

The most important points in calculating the levered centralizers are to determine the amount of force required to press the rollers against the borehole wall \( F = (F_{\text{pr}}r) \), where \( F_{\text{pr}} \) is the force of the springs about the axis of the device) and the required force of an elongate member \( (P = 2F_c \cdot \frac{H}{h} \text{[kgf]}) \), which make it possible to calculate the characteristics of elongate members: diameter, number, coil extending angle, step of torsion springs [4].

Figure 6. Floating centralizer: a) schematic for centralizers in formations with protrusions; b) schematic for centralizers in formations with cavities and gutters
For SVL tools, a lever-skid centralizing device shown in Fig. 3 is maximum approximated to computation designs. It features the calculated selection of tolerances for the dimensions of mating structural parts to exclude negative backlash effects, forces and spring sizes, providing preliminary and operational opening moment of the centralizer depending on wellbore configuration and tool weight. The tests confirmed that lever-skid centralizing devices of small-sized SVL-42S, designed to operate in cased and open boreholes with diameters from 80 to 195 mm, are favorably distinguished by reliable performance in deviated and horizontal wells, have adequate maneuverability and centralizing properties.

3.4. Calculations for centralizer placement on the tool and determination of loads

To align AL tools, it is necessary to employ two centralizers located at the upper and lower ends. The quality of centralizing as the ability of the centralizer to bear the load is estimated by the minimum effort produced by the centralizer at the maximum disclosing moment. Meanwhile, the upper centralizers have an effect from some auxiliary normal gravity elements produced by the cable thimble and cable tension forces acting at a certain angle $\varphi$ to the borehole axis [8–11].

The load on the upper centralizer is determined by the formula:

$$ R_U = \frac{q_C \sin \gamma (b_2^2 + b_3^2 + 2b_2b_3 - b_2^2)}{2b_1(b_1 + b_2 + b_3)} + \frac{q_C \sin \gamma (b_2 + b_3 + \frac{b_4}{2})}{b_2} + Q_S \left( b_2 + b_3 + \frac{b_4}{2} \right). $$

(4)

The load on the down centralizer:

$$ R_A = [(Q_c + Q_{TH}) \sin \gamma + Q_S] - R_B, $$

(5)

where $Q_S$ is secondary force; $Q_{TH}$ is gravity of the cable thimble; $Q_c$ is the gravity of the device.

The estimated load on the centralizer as a whole is:

$$ R_C = \frac{Q \sin \beta}{2}. $$

(6)

where $Q$ is the weight of the device; $\beta$ is the well angle.

Based on theoretical, design, and experimental studies as well as borehole tests, centralizing devices were classified as presented in Table 2. The classification provides an opportunity to select a centralizing device in each specific case depending on the equipment used, the wells examined and the tasks assigned.

**Table 2. Centralizing devices for acoustic logging equipment**

| Centralizing devices | LAYOUT AND APPLICATION |
|----------------------|------------------------|
|                      | Arm deflection on H, mm | Type of tool | Cased wells (diameter, mm) | Open wells (diameter, mm) |
|                      |                        |              | HST     | VW, DW<60 | DW>60, HW | HST     | VW, DW<60 | DW>60, HW |
| Kind     | Type        | Arms | Sleeve fixation | 50-127 | 152 | 264 | 152 | 264 | 50-127 | 152 | 264 | 152 | 264-164 |
|          |            |      | 86/125          | +/- | +/- | +/- | +/- | +/- | +/- | +/- | +/- | +/- | +/- |
| Laminary | Integral and face-mounted | rubber | fixed | AL 36,48 | SNL | SVL-42 |
| Lantern | Integral and face-mounted | rubber less | fixed | 86/125 | +/- | +/- | +/- | +/- | +/- | +/- | +/- | +/- |
|         | Integral and face-mounted | rubberless | loose | 86/125 | +/- | +/- | +/- | +/- | +/- | +/- | +/- | +/- | +/- |
|         | Integral and face-mounted | rubber | fixed | 81/106 | AL | +/- | +/- | +/- | +/- | +/- | +/- | +/- | +/- |
| Type                        | Description                                                                 | Table       | SNL       | +/- | -/+ |
|-----------------------------|------------------------------------------------------------------------------|-------------|-----------|-----|-----|
| Fixed                       | Hinged way to move in the axial direction                                    | fixed 81/106| +/-       |     |     |
| Loose                       | Hinged way to move in the axial direction                                    | loose 78/94 | +/-       |     |     |
| Integral                    | With rollers                                                                | AL, SNL     | +/-       | +/- | +/- |
| Unequal arms,              | Spring-loaded                                                               | 92/142      | +/-       |     |     |
| Levered Integral            | with rollers                                                                | AL, SNL     | +/-       |     |     |
| Integral                    | Face-mounted                                                                | BHTV, SVL   | +/-       | +/- | +/- |
| Skid                        | with rollers                                                                | BHTV        | +/-       | +/- | +/- |
|                             | without rollers                                                             | BHTV        | +/-       | +/- | +/- |

## 4. Conclusion

The effectiveness of various centralizer designs designated to complement acoustic logging tools was tested during down-well operations. It was necessary to select a centralizing device of such a design that would ensure good repeatability of amplitude-time parameters, thus maintaining a satisfactory maneuverability of the device in horizontal sections of the cased and open wells.

Based on the resultant data, these requirements are thought to be applicable for selecting and using centralizing devices according to the classification provided in Table 2. The amplitude repeatability error in this case is not more than 10–15% in terms of amplitude and not more than 3.5% in terms of time.

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