Application of ultrasonic phased array in acoustical logging

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Abstract

A new ultrasonic phased array transducer to increase the imaging resolution of the borehole wall is presented for acoustical logging. We fabricate a cylindrical phased array which is made up of 128 piezoelectric elements distributed on the surface of a cylinder uniformly. The working frequency of each element is 0.5MHz. Through the switch array, different combinations of the elements can lead acoustical beam rotating along the tangential direction inside the borehole. It is found that the acoustical fields can be focused very well for borehole wall imaging by dynamic focusing and good resolution can be obtained for crack testing.

Key Words: Ultrasonic phased array, dynamic focusing, acoustical logging, borehole wall imaging

1. Introduction

Ultrasonic phased array has not been really applied in acoustical logging. For the borehole wall imaging in acoustical logging, the direction and shape of the focused acoustic beams radiated by the conventional ultrasonic transducers can not be changed according to the borehole environment. The transducer has to rotate rapidly along the borehole axis as it moves in the borehole to realize scanning for all directions\(^1\)-\(^5\). The ultrasonic phased array has better imaging resolution than the conventional transducers. The planar annular phased array was theoretically presented to increase the imaging resolution\(^6\)-\(^7\). However, it also needs rotation along the borehole axis when it works.

In this paper, a new ultrasonic phased array transducer is presented for the borehole wall imaging of acoustical logging. All the piezoelectric elements are distributed on a surface of a cylinder homogeneously. Through the switch array, different combinations of the elements can lead acoustical beam rotating along the tangential direction inside the borehole. With this transducer, the acoustical beam scanning for the borehole wall can be realized by only moving the phased array transducer along the borehole axis. The mechanical rotation around the borehole axis is avoided. The cylindrical phased array transducers were also studied in other fields\(^8\)-\(^10\) in which the work environments are different to that in the borehole. Few authors studied application of the cylindrical phased array transducer for borehole wall imaging in petroleum logging.

At first, the focused acoustical field distributions in the transverse (tangential), longitudinal, and cylinder axis directions of the cylindrical phased array are investigated theoretically and experimentally. It is found that the acoustical field can be focused to a good result by the dynamic focusing and delay processing. Then, experimental study has been carried out by a cased borehole model with defects in the inner surface.

2. Cylindrical phased array transducer

The cylindrical phased array transducer for the borehole wall scanning is displayed in
Fig. 1. The transducer is made up of 128 piezoelectric elements which are distributed on the surface of a cylinder homogeneously. In the borehole scanning, the frequency of the acoustical wave cannot be too high because of the significant attenuation of the mud in the borehole. The working frequency of each element is 0.5MHz in this paper. Every element is a rectangle position with the width 20mm and height 1mm.

In fact, all the elements in the cylinder are not excited simultaneously to transmit and receive the signals. We consider \( L \) rectangle piezoelectric elements working as the active elements. This means that only \( L \) elements are used to transmit and receive the signal at a time. Through the switch array, different combination of the elements can lead acoustical beam rotating along the transverse (tangential) direction.

3. Calculation method for acoustical field

It is assumed that the wave propagates in the homogeneous and isotropic medium with the velocity \( c \), the frequency \( f \) and the density \( \rho \). The radiation acoustic pressure \( p_0 \) is given by

\[
p_0 = \frac{i \rho c}{\lambda} \int_S u e^{ikR/R} dS,
\]  

where the integration is over the complete radiating surface \( S \), \( u \) is the surface velocity of the integration element \( dS \), \( R \) is the distance between the integrating element and the observatory position in space field point, and \( \lambda \) is the wavelength.

Using Eq (1), we can calculate the radiation acoustic pressure of the transducer. However, this method will waste a lot of time in calculating. We will give another method for fast calculation of the radiation acoustic field.

For a single rectangular piston, it can be divided into \( M \) uniform little rectangular elements. It is convenient to define a right-angle coordinate system \((x, y, z)\) centred at the centre of the rectangular piston with the \( z \)-axis parallel to the axis of the cylinder. The radiation acoustic pressure of the rectangular piston can be derived as\(^{[11-12]}\)

\[
p(x, y, z) = \frac{i \rho c \Delta A}{\lambda} \sum_{m=1}^{M} \frac{u_m e^{ikR_m}}{R_m} \sin \frac{k(x-x_m)\Delta w}{2R_m} \sin \frac{k(y-y_m)\Delta h}{2R_m}.
\]  

Where \( \Delta A = \Delta h \Delta w \), \( \Delta w \) and \( \Delta h \) are the width and height respectively of the little rectangle.
element, \( R_m = \sqrt{z^2 + (x-x_m)^2 + (y-y_m)^2} \). In this paper, the rectangle elements with uniform excitation are considered, and \( u_m \) is the same for all elements. The center of \( m \)th element is denoted by \((x_m, y_m)\).

For simply, the radiation acoustic pressure \( p_j \) of the \( j \)th element is rewritten as

\[
p_j = A_j e^{i\Delta \phi_j},
\]

where \( A_j \) and \( \Delta \phi_j \) are the amplitude and phase of the \( j \)th element, which can be determined by Eq. (2). In order to keep all waves from each element arrive at the desired point in phase, we should add a delay phase \( -\Delta \phi_j \) for \( j \)th element. Therefore, the phased acoustic pressure from \( L \) active elements is expressed as

\[
p(r, \theta, z) = \sum_{j=1}^{L} p_j e^{i\Delta \phi_j},
\]

and the phased acoustic field is focused at the desired point that is named focus. Using Eq. (4), we can calculate the focused radiation acoustic field of the transducer.

**4. The acoustical field distributions of the transducer**

We measured the focused phased array acoustical field of the transducer and also obtained the theoretical results. Fig. 2 displays the acoustical field distributions in the transverse (tangential) and longitudinal directions when the active element number \( L \) is 16 and the focal distance is 90mm. The solid and dotted lines represent the theoretical and experimental results respectively. It can be found that the theoretical curves accord with the experimental curves very well. There is definite difference between the positions of the theoretical focus to that of experimental focus. However, their shape and structure are the same. It can be also found that the tangential field has a narrow -3dB width and a good focused characteristic. The acoustical wave can be focused as a beam with a narrow width and long depth. It is very useful to the exploration in the borehole.

Fig. 2 The acoustical field distributions in the transverse (a) and longitudinal (b) directions when the active element number \( L \) is 16 and the focal distance is 90mm.
We also measured the acoustical field distribution in the cylinder axis direction. It is shown in Fig. 3. It is easy to find that the acoustical field has a wider width in the cylinder axis direction. The cause is that the acoustical field has no focused characteristic of the phased array in this direction.

Fig. 3 The acoustical field distribution in the cylinder axis direction when the active element number $L$ is 16 and the focal distance is 90mm. The solid and dotted lines represent theoretical and experimental results, respectively.

5. Scanning and imaging in the borehole

The scanning and imaging experiments are conducted in a model of a cased borehole. We made 13 cracks with width of 2mm in a cased borehole with diameter of 152mm (see Fig. 4). These cracks are difficult to be measured by the conventional transducers. Fig. 5 is the waveform amplitude of the scanning in a circle by the phased array transducer. Fig. 6 gives the imaging of the cased borehole by the waveform amplitude of the scanning. It can be seen by Figs. 5 and 6 that 13 cracks can be revealed distinctly.

Fig. 4 The cased borehole with 13 cracks.
Fig. 5 The waveform amplitude of the scanning in a circle for the cased borehole by the phased array transducer.

Fig. 6 The imaging of the cased borehole with 13 cracks.

6. Conclusions

A new ultrasonic cylindrical phased array transducer is designed for borehole wall imaging in petroleum logging without instrument rotation. Comparing with the conventional rotated transducers, it can decrease the mechanical complexity greatly. The focused characteristic of the radiation acoustic field of the cylindrical phased array is studied numerically and experimentally.

Through the switch array, different combinations of the elements can lead acoustical beam rotating along the tangential direction inside the borehole. The acoustical wave can be focused as a beam with a narrow width and long depth. It is very useful to the exploration in the borehole.

The cylinder transducer with work frequency 0.5MHz can test the cracks, which can not be tested by the conventional transducers in the same conditions, with width of 2mm in the cased borehole with diameter of 152mm.

This study lays a theoretical and experimental groundwork for the application of phased array technology in petroleum logging.

References


