

Coupling of elastic waves and voltage waveforms in monopole ALWD: role of piezoelectricity and acoustic propagation

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Abstract: Acoustic Logging While Drilling (ALWD) acoustic measurement, characterized by combining drilling and logging operations, is widely used to obtain elastic parameters of formation surrounding the borehole. Most published simulated monopole acoustic LWD waveforms are typically represented by acoustic pressure. However, these pressure waveforms do not match the voltage waveforms recorded experimentally. To investigate this discrepancy, we employed the finite element method to comprehensively calculate both the piezoelectric effects of transducers and acoustic wave propagation, obtaining voltage waveforms and mechanical waveforms. Quantitative comparisons between mechanical and voltage waveforms reveal that the output voltage does not represent pressure signals alone but rather constitutes a combination of multiple mechanical signals. Based on piezoelectric equations and the structure of piezoelectric transducers used in this study, we systematically investigated the coupled effects of four mechanical quantities on output voltage: radial strain and axial stress (reflecting formation information), as well as acoustic pressure and radial displacement in borehole fluid (indicating interference effects from measurement tools). Further analysis explores the respective contributions of these four mechanical quantities to different wave groups. This research provides valuable insights for understanding the coupling mechanisms between elastic waves in logging applications.

Keywords: Acoustic logging while drilling (LWD), boundary condition, piezoelectric effect, elastic waves, voltage waveforms

Methods

To better understand the relationship between mechanical quantities and the voltage received by the transducer, we've built a FEM model that combines the piezoelectric effect and acoustic wave propagation [Zhang 2021]. This integrated approach covers the entire process from voltage signal generation to acoustic wave propagation and back to voltage signal reception. In the radial direction, the FEM model is divided into four parts: the fluid inside the collar, the collar itself, the fluid outside the collar, and the formation.

The acoustic LWD tool includes a transmitting transducer and a receiving transducer placed 3 m apart. Both transducers, with identical geometric structures and surrounded by epoxy seals, are shallowly embedded in the outer surface of the drill collar. These tubular piezoelectric transducers are radially polarized. The inner wall of the piezoelectric ceramic tube is grounded, while the outer wall is connected to the excitation voltage.

In our multiphysics coupling model, we simultaneously simulate the acoustic field within the borehole fluid, the elastic field in solid materials, and

the coupled mechanical and electrostatic fields in the piezoelectric ceramic tube. For boundary conditions, the fluid's far-field boundary employs a plane-wave-radiation condition [Givoli 2004] and the solid's far-field boundary uses a low-reflecting condition [Lalanne 2000]. Both designs aim to minimize boundary reflections that could interfere with the simulation results. The mesh utilizes a free quadrilateral pattern. The maximum element size is determined by $v/(6f_0)$, where v represents the minimum wave velocity among all model materials, and f_0 denotes the center frequency of the excitation voltage. Model parameters and material properties are detailed in Tab. 1.

Fig. 1 presents the process of acoustic wave generation, propagation, and reception. When an excitation voltage signal is applied to the transmitter's outer electrode, the transmitter utilizes the inverse piezoelectric effect to convert the input voltage signal into various mechanical signals like strain ϵ , stress σ , displacement u , particle velocity v , and particle acceleration a . The generated acoustic waves then propagate through the borehole and formations to reach the receiver. At the receiver, these mechanical

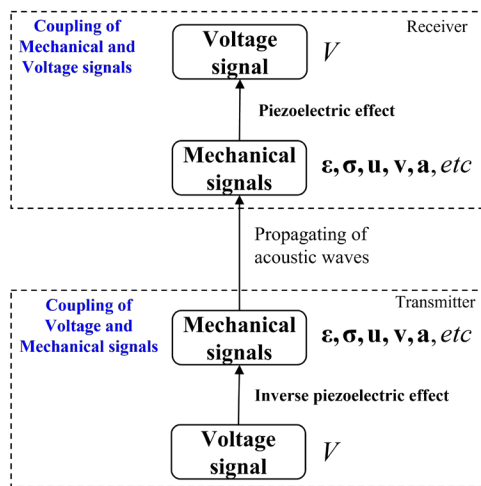


Fig. 1: The coupling process of excitation, propagation, and reception.

signals, which contain information about the borehole and formations, are transformed back into voltage signals via the piezoelectric effect and then outputted. Both the transmitter and receiver involve the coupling of elastic and voltage waveforms.

Tab. 1: Materials and geometric parameters of fluid, drill collar, piezoelectric transducer and formation

Component	ρ (kg/m ³)	v_p (m/s)	v_s (m/s)	Thickness (m)	Height (m)
Inner fluid	1000	1470	–	0.027	$+\infty$
Drill collar	7800	5860	3131	0.063	$+\infty$
PZT-5H	7500	4118	1751(SV) 1770(SH)	0.006	0.088
Epoxy	1500	3089	1589	0.010	0.120
Outer fluid	1000	1470	–	0.027	$+\infty$
Formation	2320	3970	2455	$+\infty$	$+\infty$

Waveforms difference between mechanical quantities and voltage

This section calculates the pressure, radial displacement, and voltage waveforms, considering the transducer's piezoelectric effect and acoustic wave propagation. To explore their differences and similarities, we set up three models:

Model 1: The tube transducer is slightly indented 0.063 m from the collar's external surface, with the collar in infinite fluid.

Model 2: The tube transducer is slightly indented 0.063 m from the collar's external surface, with the collar in a borehole.

Model 3: The tube transducer is slightly indented 0.050 m from the collar's external surface, with the collar in a borehole.

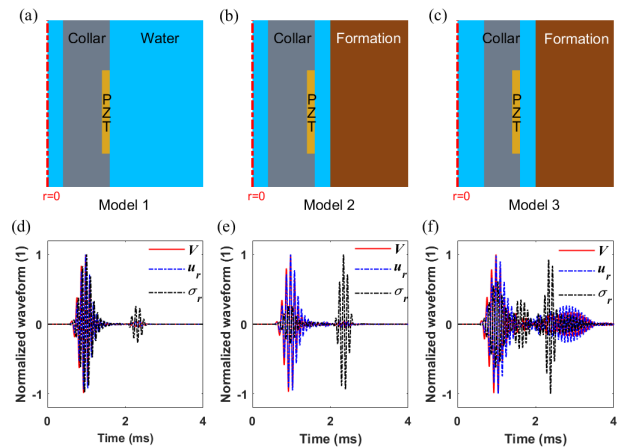


Fig. 2: The schematics of the three models show the voltage, radial displacement, and radial stress (negative pressure) waveforms. Figures (a) and (d) depict collars with a thickness of 0.063 m in infinite fluid. Figures (b) and (e) show collars with a thickness of 0.063 m in infinite boreholes. Figures (c) and (f) illustrate collars with a thickness of 0.050 m in boreholes. The voltage source has a center frequency of 10 kHz.

The voltage source used for the transmitting transducer is a cosine envelope pulse centered at 10 kHz. At the outer surface center of the receiver, the normalized waveforms of voltage, radial stress (negative pressure), and radial displacement were calculated. Fig. 2 presents the schematics of the three models and their corresponding normalized waveforms. Each waveform clearly shows two distinct waves: the collar wave and the Stoneley wave, ordered by their arrival time. In all three FEM models, the voltage waveforms exhibit similar characteristics, with a strong collar wave followed by a weak Stoneley wave. This pattern aligns with the voltage waveform characteristics observed in experimental recordings [Zhu 2008].

In Fig. 2d, with the collar in infinite fluid, both the pressure and radial displacement waveforms display a dominant collar wave and a minor Stoneley wave, mirroring the cosine waveform. In Fig. 2e, when the collar is positioned in a borehole, the radial displacement waveform continues to show a strong collar wave and a weak Stoneley wave, aligning with the voltage waveform. However, the pressure waveform in this case exhibits a weak collar wave and a strong Stoneley wave, conflicting with the voltage waveform. Comparing Fig. 2d and Fig. 2e reveals that the disparity between the voltage and pressure waveforms increases when a formation is present, primarily reflected in the relative amplitude of the collar wave. In Fig. 2f, a thinner collar in the borehole produces waveforms similar to those in Fig. 2e. The comparison

between Fig. 2e and Fig. 2f shows that even with a reduced collar thickness, the voltage and pressure waveforms still exhibit significant differences, mainly in the relative amplitude of the collar wave.

Relation between four mechanical quantities and voltage

As established in the previous section, voltage is more likely to be generated from a combination of multiple mechanical quantities rather than a single one. This raises two key questions: which specific mechanical quantities are involved in this conversion, and what are the respective weights of these quantities? To address these questions, this section delves into the piezoelectric equations for an in-depth exploration.

$$\begin{cases} \varepsilon_\theta = s_{11}^E \sigma_\theta + s_{12}^E \sigma_z + s_{13}^E \sigma_r + d_{31} E_r \\ \varepsilon_z = s_{12}^E \sigma_\theta + s_{11}^E \sigma_z + s_{13}^E \sigma_r + d_{31} E_r \\ \varepsilon_r = s_{13}^E \sigma_\theta + s_{13}^E \sigma_z + s_{33}^E \sigma_r + d_{33} E_r \end{cases} \quad (1)$$

Here, s_{1i} , $i = 1, 2, 3$, and d_{3j} , $j = 1, 2, 3$, represent the compliance coefficient and piezoelectric constant of the piezoelectric ceramic tube, respectively. E_r denotes the radial electric field intensity, ε represents strain, and σ indicates stress. The subscripts r , z , and θ correspond to the radial, axial, and circumferential components, respectively.

For a radially polarized thin tube piezoelectric transducer,

$$V = \delta E_r \quad (2)$$

$$\varepsilon_\theta = \frac{u_r}{r} \quad (3)$$

Here, δ denotes the thickness of the piezoelectric ceramic, and r represents the distance between the outer wall of the transducer and the borehole axis.

Thus, the voltage V can be expressed in terms of four mechanical quantities selected from u_r , ε_z , ε_r , σ_θ , σ_z , and σ_r . Note that these mechanical quantities pertain to the piezoelectric ceramics in the transducer. However, in acoustic LWD, the transducer is intended to sense the mechanical quantities of the borehole fluid. According to the boundary conditions, radial displacement u_r and radial stress σ_r are continuous between the transducer and the borehole fluid, making them representative of the borehole fluid's mechanical quantities. Additionally, radial strain ε_r and axial strain ε_z have shown high similarity to voltage waveforms, making them preferable candidates. Consequently, u_r , σ_r , ε_r , and ε_z are chosen to represent the voltage, and the expression for V is obtained as follows:

$$V = V_1 + V_2 + V_3 + V_4 \quad (4)$$

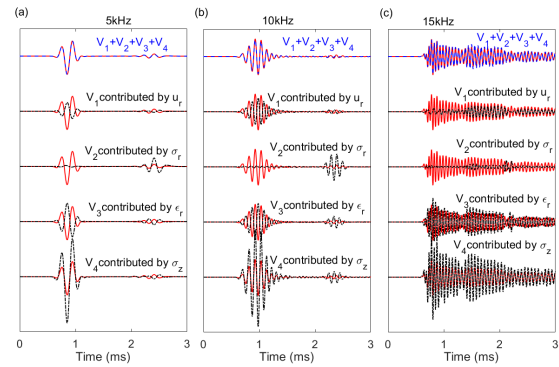


Fig. 3: The contributions of u_r , σ_r , ε_r , and σ_z to voltage V at three distinct center frequencies: (a) 5 kHz, (b) 10 kHz, and (c) 15 kHz, are analyzed. The black dotted lines denote the voltage components V_1 , V_2 , V_3 , and V_4 , which are contributed by u_r , σ_r , ε_r , and σ_z , respectively. The blue dashed lines illustrate the combined sum of these four voltage components. For comparison, the red solid lines indicate the actual voltage V recorded by the transducer.

with,

$$\begin{aligned} V_1 &= \frac{s_{13} \delta}{r (s_{13} d_{31} - s_{11} d_{33})} u_r \\ V_2 &= -\frac{(s_{13}^2 - s_{11} s_{33}) \delta}{s_{13} d_{31} - s_{11} d_{33}} \sigma_r \\ V_3 &= -\frac{s_{11} \delta}{(s_{13} d_{31} - s_{11} d_{33})} \varepsilon_r \\ V_4 &= -\frac{s_{13} (s_{12} - s_{11}) \delta}{s_{13} d_{31} - s_{11} d_{33}} \sigma_z \end{aligned} \quad (5)$$

Eq. (4) presents the voltage V obtained by substituting Eq. (1) and Eq. (3) into Eq. (2). Eq. (5) depicts the voltage components associated with the four mechanical quantities illustrated in Fig. 3. For a transducer with a known material composition and dimensions, the weight coefficients of these mechanical quantities in the voltage components are well-defined. At the boundary between the transducer and the borehole fluid, the radial displacement of the transducer equals that of the fluid, and the transducer's negative radial stress corresponds to the fluid's acoustic pressure. Hence, the first two voltage components in Eq. (4) represent the weighted radial displacement and acoustic pressure of the borehole fluid, offering insights into borehole and formation characteristics. Conversely, the last two components reflect the transducer's radial strain and axial stress, which indicate tool-related interference. To enhance formation information and mitigate tool interference, the material properties and dimensions of the transducer can be optimized. This optimization aims to increase the

weighting of the first two voltage components while reducing the weighting of the last two in Eq. (4).

Eq. (5) presents how u_r , σ_r , ε_r , and ε_z contribute to the voltage. We computed the waveforms of these four voltage components under different voltage excitation center frequencies, results shown in Fig. 3. The figure includes the waveforms of the four mechanical quantities and voltage. The black dash - dotted lines indicate the voltage components V_1 , V_2 , V_3 , and V_4 from u_r , σ_r , ε_r , and ε_z , calculated by weighting the mechanical quantity waveform data per Eq. (5). The blue dashed line shows the sum of the four voltage components ($V_1 + V_2 + V_3 + V_4$), and the red solid line represents the voltage waveform V from the finite element model.

From the top waveforms (red and blue lines) in each subplot of Fig. 3, it is evident that the voltage waveform V at different frequencies aligns with the waveform of the total four voltage components. This matches the result in Eq. (4). Comparing the amplitudes of the voltage waveform and the four voltage component waveforms (red line vs. black lines) shows that u_r , ε_r , and σ_z significantly contribute to the drill collar wave and are key for studying its characteristics. Meanwhile, σ_r has a smaller contribution to the drill collar wave but a larger one to the Stoneley wave. This might relate to using the Stoneley wave to invert formation permeability.

Conclusions

By considering both the piezoelectric effect of the transducer and the propagation of the acoustic wave, we simulate the mechanical responses and output voltage in monopole acoustic LWD. The main conclusions include the following:

The output voltage recorded by the transducer results from an acoustic-voltage coupling process, jointly contributed by multiple mechanical quantities via the piezoelectric effect rather than a single physical parameter. Borehole fluid radial displacement and radial stress carry formation information, while transducer radial strain and axial stress reflect tool interference. This coupling mechanism necessitates receiver designs that amplify the weighting factors of formation-information carriers (radial displacement/stress) during electroacoustic transduction, while suppressing the coupled influence of tool-interference terms (radial strain/axial stress) to effectively extract target formation signals.

Decoupling the contributions of individual mechanical quantities to the output voltage waveform reveals that the acoustic-voltage coupling selectively reconstructs waveform features. The collar wave is dominated by strong coupling pathways from borehole fluid radial displacement, transducer radial strain, and

axial stress, whereas the Stoneley wave is primarily governed by a specific coupling channel from borehole fluid radial stress. This demonstrates how differential coupling intensities of mechanical quantities during electromechanical conversion directly shape the voltage waveform's characteristic amplification of collar waves and suppression of Stoneley waves.

Acknowledgments

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