Understanding Logging-While-Drilling Transducers with COMSOL Multiphysics® Software

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Abstract: Logging-while-drilling (LWD) acoustic transducers provide real-time data about the geologic and geophysical properties of the borehole that ensure safety margins and optimize completion. It is important to understand what causes the different resonance modes in the transmitter and obtain relevant acoustic response information to assist new designs and field applications of the transmitter. COMSOL simulation allows investigation of different designs at a low cost. In this paper, we provided a complete procedure using COMSOL Piezoelectric Devices and Acoustic-Piezoelectric Interaction modules to obtain displacement resonance response, acoustic field distribution, absolute acoustic pressure frequency response, transmitting voltage response, and directivity. We also showed how to get receiving sensitivity for a receiver.

Keywords: LWD, acoustic logging, transmitter, receiver, COMSOL

1. Introduction

Acoustic logging has become an integral part of wireline logging, compensating with its own advantage of real-time measurements. [1] Engineers use acoustic data from sonic logging tools to drill more efficiently with greater safety margins and to optimize completion. Sonic acquisition is challenging while drilling; however, service companies have worked to develop LWD sonic tools because they provide information that is not readily available from other logging devices while drilling. Measurements derived from the propagation of sound waves (Figure 1) through porous media provide helpful information about geologic and geophysical properties. Petrophysicists have developed methods to use real-time acoustic measurements to determine formation attributes that include pore pressure and overburden gradients, lithology and mechanical properties. Petrophysicists also use sonic data for gas detection, fracture evaluation and seismic calibration. [2]

Three types of acoustic sources, monopole, dipole, quadrupole, are used in well logging for different in-field applications. Real-time data from monopole sources have two main applications for pore pressure determination: identifying overpressured formations and selecting mud density [2]. Dipole sources can generate shear waves that help reservoir engineers to know tectonic and wellbore stresses and their direction. These properties first affect wellbore stability (breakouts), and then the ability to hydrofracture the well to improve production. [3] Significant changes happen around faults, changing formations, fractures,

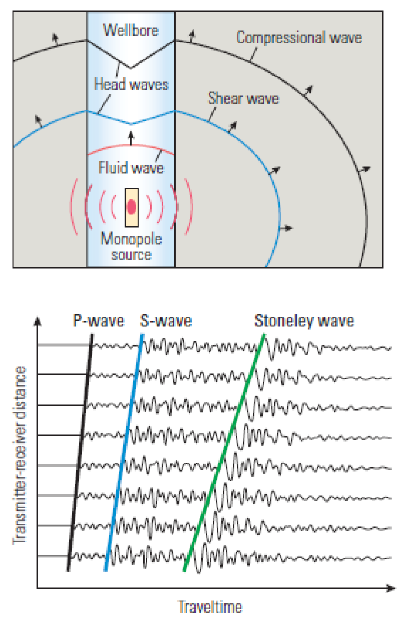

Figure 1. Sonic waves from monopole sources. Monopole sonic tools generate a pulse of energy that strikes the formation and then travels along the borehole as a compressional head wave. Current tools have multiple receivers, and the sonic signal arrives later as the transmitter-receiver distance increase. Although the signal amplitude diminishes with distance between transmitter and receiver, data can be time shifted and stacked to improve coherence and signal-to-noise ratio. [2]

and rock deformations and can be detected by shear-wave anisotropy as well. [3] Advanced sonic tools can also be used for imaging. Sonic imaging uses reflected P-waves to detect reflectors that are subparallel or at low angle relative to the borehole. [4] Now there is a general consensus in the industry that the best way to measure slow formation shear in the LWD environment is by utilizing quadrupole waveforms. [5]

With COMSOL, different designs can be simulated at a low cost so it makes a worthy tool for LWD acoustic transducer design. Both pzd and acpz modules were used. One of the important usages of COMSOL in this field is to simulate a specific transmitter design so that it can be understood what contributes to the various resonance peaks it has. COMSOL simulations can also provide abundant information on acoustic response which can assist the field application of the transmitter. In this paper, we provided a systematic method how to use COMSOL to understand different resonance modes of a transmitter and obtain important acoustic information such as acoustic field distribution, absolute acoustic pressure frequency response, transmitting voltage response, and directivity. We also researched into the receiver designs, giving a methodology for obtaining and explaining the receiving sensitivity. These results will help with the LWD acoustic transducers design in general.

2. COMSOL Multiphysics

The entire analysis of the receiver was completed in the Piezoelectric Devices (pzd) module under Structural Mechanics. The displacement analysis part of the transmitter was also conducted in this module. The acoustic response analysis part of the transmitter was done in the Acoustic-Piezoelectric Interaction, Frequency Domain (acpz) module under Acoustics, Acoustic-Structure Interaction. All of them were studied in the frequency domain.

2.1 Geometry

The design of the transmitter (Figure 2) consists of eight pieces of PZT-5A ceramics wrapped in epoxy and anti-corrosive rubber. Between two ceramic pieces is 20 mm spacing in the arc length direction and 5 mm spacing in the height direction. The receiver design (Figure 3) features a number of small pieces of PZT-5A, each piece being separated by epoxy.

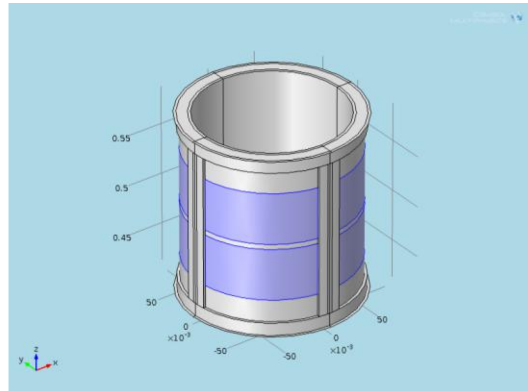

Figure 2. Entire geometry of the transmitter featuring the PZT part (highlighted). There are 8 pieces of PZT pieces in total.

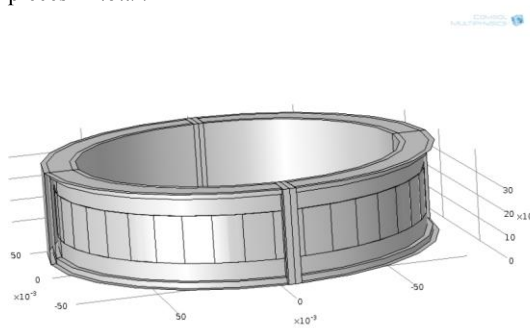

Figure 3. Entire geometry of the receiver. There are a number of small pieces of PZT separated by epoxy.

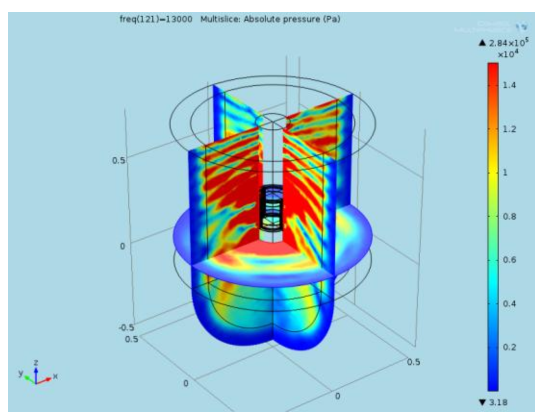

Figure 4. Acoustic pressure field plot for the transmitter. It highlights the geometry for the acoustic studies of the transmitter with a cylindrical and half-spherical water domain and corresponding perfectly matched layers.

To simulate the acoustic characteristics of the transmitter, it was installed on a solid steel shaft to represent the drill. It was covered with a steel ring for protection against abrasion. A cylindrical and half-spherical water domain was added along with respective perfectly matched layers to eliminate reflections from the sides and the bottom. The geometry, which is shown in Figure 4 as the acoustic pressure field plot, represents the borehole structure most realistically with reasonable simplifications.

2.2 Governing Equations

For the pzd module frequency domain, the governing equations are:

$$-\rho\omega^2\mathbf{u} - \nabla\cdot\boldsymbol{\sigma} = \mathbf{F}_{\mathrm{V}}e^{i\phi} \qquad (2.2.1)$$

$$\nabla\cdot\mathbf{D} = \rho_{\mathrm{V}} \qquad (2.2.2)$$

For the displacement analysis of the transmitter design, the total displacement TD, the radial displacement RD, and the Z displacement ZD, are defined as:

$$\begin{cases} \mathrm{RD} = \mathrm{sqrt}\ ((\mathrm{pzd.uAmpX})\text{^}2 + (\mathrm{pzd.uAmpY})\text{^}2) \\ \mathrm{ZD} = \mathrm{pzd.uAmpZ} \\ \mathrm{TD} = \mathrm{sqrt}\ (\mathrm{RD}\text{^}2 + \mathrm{ZD}\text{^}2) \qquad (2.2.3) \end{cases}$$

For the acpz module frequency domain, the governing equations are as below in addition to equations 2.2.1 and 2.2.2.

$$\nabla\cdot -\frac{1}{\rho_c}\left(\nabla p_t - \mathbf{q}_d\right) - \frac{k_{eq}^2 p_t}{\rho_c} = Q_m \qquad (2.2.4)$$

$$p_t = p + p_b \qquad (2.2.5)$$

$$k_{eq}^2 = \left(\frac{\omega}{c_c}\right)^2 \qquad (2.2.6)$$

The absolute acoustic pressure is acpz.absp, and far field sound pressure level is acpz.ffc1.Lp_pfar.

The sound pressure level (SPL) is defined as:

$$\mathrm{SPL} = 20\log_{10}(p/1\mu Pa) \qquad (2.2.7)$$

The transmitting voltage response (TVR) definition for 1m down the center of the steel shaft is:

$$\begin{cases} p_{\mathrm{rms}} = \mathrm{sqrt}\ (0.5*\mathrm{pfar}(0,0,-1)*\mathrm{conj}(\mathrm{pfar}(0,0,-1)))\ [\mathrm{Pa}] \\ \mathrm{TVR} = 20*\log10(p_{\mathrm{rms}}/\mathrm{V}_{\mathrm{rms}}/1[\mu\mathrm{Pa/V}]) \qquad (2.2.8) \end{cases}$$

For the receiver, since it is the same pzd module, the governing equations are the same with 2.2.1 and 2.2.2. For the receiving sensitivity (RS), receiving voltage (RV) is obtained by

$$\mathrm{RV} = \mathrm{intop1(pzd.normJ)/(pzd.omega*C)} \qquad (2.2.9)$$

where current density pzd.normJ is integrated on a boundary to get current, pzd.omega is the angular frequency, and C is the capacitance of a PZT piece. To get voltage of several ceramics pieces in series, one can simply sum the voltages up.

And RS is then obtained by

$$\mathrm{RS} = 20*\log10(\mathrm{RV}/(\mathrm{P}*1\ [\mathrm{V}/\mu\mathrm{Pa}])) \qquad (2.2.10)$$

2.3 Boundary Conditions

The transmitter is working in d_{31} mode. The poling is in the radial direction, the ground boundaries are the inside of all the PZT pieces and the voltage boundaries are the outside of all the PZT pieces. The poling is defined with a base vector system given in Table 1.

Table 1. Radial poling base vectors.

	x	y	z
x1	-sin(atan2(Y,X))	cos(atan2(Y,X))	0
x2	0	0	1
x3	cos(atan2(Y,X))	sin(atan2(Y,X))	0

Besides PZT, all other materials are treated as linear elastic materials. Isotropic damping factor for PZT is 0.001, for epoxy is 0.01, and for rubber is 0.05. The isotropic dielectric loss factor for PZT is 0.01.

The acoustic model has the same ground, voltage and poling conditions. There are additional fixed boundaries that are the top boundaries of the steel shaft, and far field boundaries that are the boundaries between water domains and perfectly matched layers. There is a far field calculation with the far-field variable name pfar.

The steel is also treated as linear elastic material with an isotropic damping factor of 0.001.

For the receiver operating in d_{31} mode, its boundary conditions are similar to those of the transmitter. One difference is that the receiver has a periodic boundary load on the top, bottom, and side boundaries. The ground boundaries are still the inside of the PZT pieces for reference. The voltage boundaries are integrated to obtain receiving voltages and for d_{31} mode, they are on the outside of the PZT pieces. No source voltage is applied.

3. Results and Discussions

For the transmitter design, the displacement as defined in equation (2.2.3) of a representative domain point probe is plotted in Figure 5. The analysis of each resonance peak is as below.

2.4 kHz, ring resonance frequency; 4.8 dipole ring mode; 9.6 kHz quadrupole ring mode (not visible due to another 10 kHz mode);

4.9 kHz, 5.1 kHz, 5.3 kHz, broadened longitudinal resonance frequencies with the main one caused by the arc length of the half ring;

8 kHz, 10 kHz, both are longitudinal resonance frequencies in the height direction; 8 kHz caused by the height of the entire cylinder, and 10 kHz a major acoustic impedance mismatch length (bottom of the cylinder to the top of the upper PZT piece, or top of the cylinder to the bottom of the lower PZT piece); they feature strong Z displacement and weak radial displacement;

11.5 kHz, longitudinal resonance frequency caused by the PZT piece arch length (lower than 13 kHz because of the composite); it features strong radial displacement and weak Z displacement;

15 kHz, third harmonic by the 4.9 kHz, 5.1 kHz, and 5.3 kHz; because three resonances come in together, it is a very strong peak. They feature strong radial displacement and weak Z displacement. The three Z displacement components are still visible.

The collaborative resonance response of the transmitter on the drill is best characterized by the absolute acoustic power of some representative water domain points, which is shown in Figure 6. It matches the displacement resonance response in that it characterizes such peaks as caused by half ring resonance around 5 kHz, height resonance around 8 kHz, PZT arc length resonance around 11.5 kHz, and collective third harmonic resonance around 15 kHz. This makes sense as displacement resonance causes the peak acoustic response.

The transmitting voltage response (TVR) plot shows how effective the transmitter is to convert electrical energy into detectable acoustic energy. Based on equation (2.2.7), the TVR for this transmitter is plotted in Figure 7 against frequency. TVR peaks correspond to resonance peaks and there are major peaks from 8 to 10 kHz and 13 to 15 kHz. This proves that at displacement resonance peaks, TVR has the maxima.

The directivity of the transmitter is also a very important criterion because information in all directions is sought. The directivity is characterized by SPL as defined in equation (2.2.7) in the azimuthal view. +/-10 dB range is considered as good directivity. This transmitter has a satisfactory directivity as shown in Figure 8 at various frequencies.

For the receiver, the most important parameter is receiving sensitivity (RS). As depicted in equation (2.2.10), the RS plot is given in Figure 9. Good receivers should have a relatively flat RS. However, since this receiver has the half ring resonance and other resonances, there are some fluctuations in the RS curve, especially around 5 kHz, 8-10 kHz, 11.5 kHz, and 15 kHz. It is a limited range of value though.

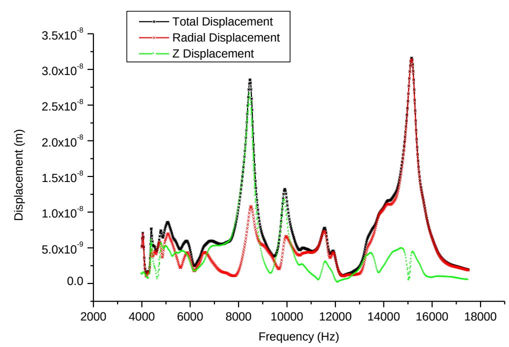

Figure 5. Displacement frequency response of the transducer design. There are multiple resonance peaks caused by different reasons.

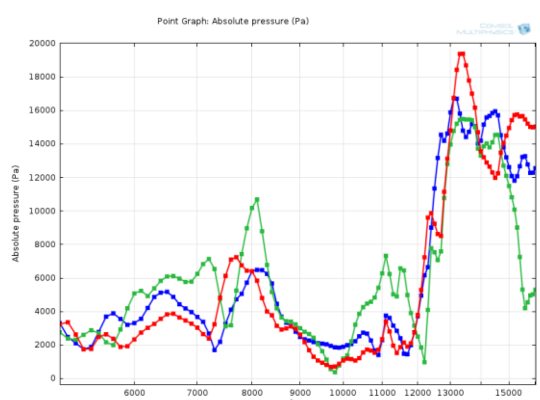

Figure 6. Absolute acoustic pressure of four points in the water around the drill w.r.t. frequency. It matches the displacement resonance.

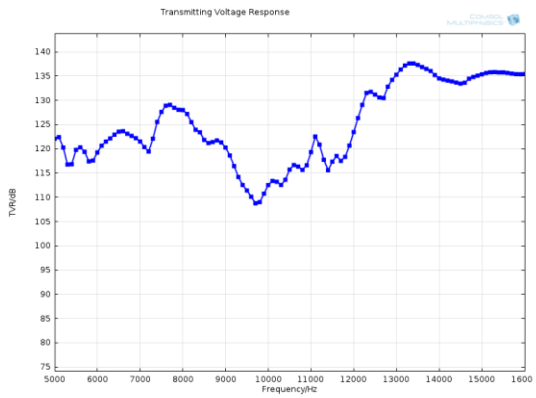

Figure 7. TVR w.r.t. frequency. TVR peaks appear at resonance peaks.

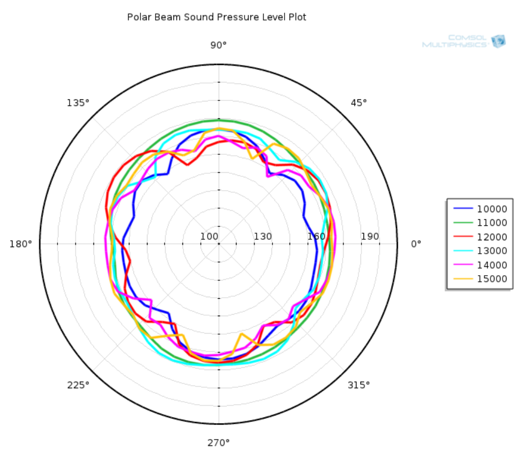

Figure 8. Polar beam pattern of SPL for different frequencies to show directivity. Overall, the device demonstrates good directivity with +/- 10 dB fluctuation around the center SPL.

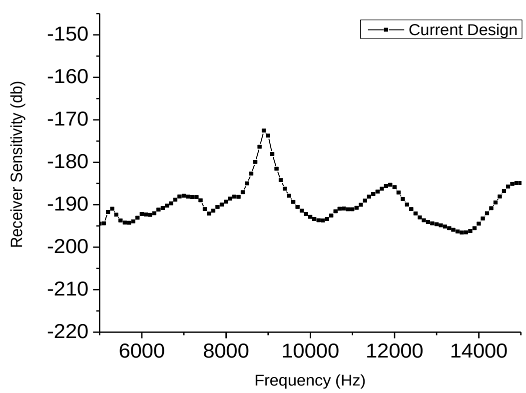

Figure 9. Receiving sensitivity of the receiver, d_{31} mode. It has a limited range of values but it changes to the resonance response.

4. Conclusion

Detailed COMSOL simulations give a trustworthy guideline what transmitter and receiver designs meet requirements for the LWD acoustic applications. Explanations for different resonance peaks in the transmitter were given in this paper and they could be of reference for designing new transmitters if certain peaks are desired or unwanted. Acoustic response analysis gave much information for applying the transmitter in practice such as acoustic field distribution, absolute acoustic pressure frequency response, transmitting voltage response, and directivity. For the receiver, the receiving sensitivity was given and explained. COMSOL results are useful in understanding the devices and they give guidance for their in-field applications.

Acknowledgements

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