CHIN. PHYS. LETT. Vol. 33, No. 7 (2016) 074301

Optimization Design for the Sandwich Piezoelectric Transmitters in Acoustic Logging *

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(Received 28 April 2016)

An optimized transducer prototype with a sandwich structure vibrated longitudinally is proposed for a transmitter in acoustic logging, especially in acoustic logging while drilling, by taking account of drilling environments with high temperature and pressure, as well as strong collar drilling vibration during the drilling process. Aimed to improve the transmitting performance, numerical and experimental studies for the transducer optimization are conducted. The impact of location and length of the piezoelectric stack on resonance characteristics and effective electromechanical coupling coefficient is calculated and analyzed. Admittance and transmitting performance of the proposed transducer are measured in laboratory experiments, and the results are compared with simulated ones. It is shown that the newly proposed transducer has higher transmitting performance with lower resonance frequencies. This work provides theoretical and experimental bases for transducer designing and acoustic wave measurements in acoustic logging, especially in acoustic logging while drilling.

PACS: 43.38.+n DOI: 10.1088/0256-307X/33/7/074301

Acoustic logging while drilling (LWD) has wide applications in offshore petroleum exploration due to increasing demands of logging in highly deviated and horizontal drilling wells. Formation properties, such as anisotropy, permeability, as well as porosities can be derived from full acoustic waveforms, such as from longitudinal and transverse wave velocities, and the Stoneley wave amplitudes measured acoustically during the drilling process.[1,2] Different from conventional wire-line acoustic logging, in acoustic LWD, the drilling pipe occupies most of the space inside the bore well. Acoustic wave propagations were seriously impacted by the noises that mainly come from collar waves, drilling and fluid noises, and so on.[3] Longitudinal wave velocity measurement was initially realized by monopole acoustic LWD.[4,5] It was reported that collar waves are the leading components during longitudinal acoustic LWD.[6−8] Most monopole acoustic LWD transmitters used in drilling operation are piezoelectric cylindrical tube formed by splicing tiles.[9−11] Using the radial and flexural vibrational modes, the transmitter has advantages with a large power and collar wave suppressor. However, it is difficult to assemble and also it is fragile.

Sandwich piezoelectric transducers have the advantages of simple structure, anti-vibration, easy implementation, high electroacoustic power.[12] Numerous reports were focused on the vibrational theory and design used in underwater acoustic and ultrasonics.[13−15] However, it seems that few works are reported in well logging. The longitudinal vibrated piezoelectric rod used as monopole source in acoustic LWD was seen in 1995.[16] The frequency band of the piezoelectric rod is narrow with around 11–13 kHz. Our previous work is shown for bidirectional radiational sandwich piezoelectric transmitter in acoustic LWD by Cong *et al.*[17] However, collar wave interference exists due to the incomplete insulation between the transducer and the collar. Moreover, the performance of this kind of transducer, especially its transmitting voltage response, is lower. Thus it is necessary to further optimize for improvement of transmitting efficiency.

In this Letter, a bidirectional sandwich piezoelectric transducer is optimally designed by numerical simulation and experiments. The resonance and antiresonance frequency equations are derived by using equivalent circuit analysis. By using the finite element method (FEM), the resonance frequency and effective electromechanical coupling coefficient are numerically calculated with respect to piezoelectric location and length. The prototype transducers are prepared and tested. Admittance and experimental borehole model performance results demonstrate that our optimized transducer gives a lower resonance frequency and higher transmitting power that would be valuable for acoustic LWD research and development.

The structural scheme of bidirectional sandwich piezoelectric transducer is shown in Fig. 1. The transducer consists of a metal mass in the middle, two sets of piezoelectric stacks and two radiation masses. Each piezoelectric stack is formed by n pieces of piezoelectric wafers with thickness of l_{p}, and the total length of each piezoelectric stack is L_{p}. Here R_1 and S_1 represent the radius and area of middle mass and piezoelectric ceramics, R_2 and S_2 represent the radius and area of radiation mass, and l_{h} and l_0 represent the length of radiation and middle mass, respectively.

*Supported by the National Natural Science Foundation of China under Grant Nos 41474160 and 11304347.
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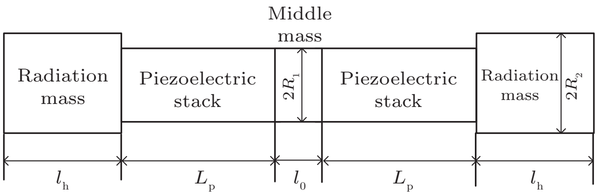

Fig. 1. Structural scheme of the bidirectional sandwich piezoelectric transducer.

The transducer is mounted on the drill collar with a hollow cylinder structure, i.e., for the collar with outside diameter of 171.45 mm. For the new type transducers, the mud fluid pass structure inside the drilling collars is changed into two branches, thus the solid space is left for mounting the transducers. In this case, the transducer is plugged in a through an empty hole vertical to the axial direction of the drill collar. The total length of the transducer is 170 mm, that is nearly the same as the outside diameter of the collar. Two protective covers are arranged outside the radiation surfaces of the transducer. O-shape rubber rings fill between the transducer and the drill collar to weaken the collar waves. Also, these O-shape rings are used for sealing the empty space between the transducer bar and the collar. Acoustic waves radiate to the bore hole through both radiation surfaces when the transducer vibrates longitudinally. The transducer is theoretically analyzed by the equivalent circuit method based on the thin rod hypothesis. With a constant total length, the resonance and anti-resonance frequency equations of the bidirectional transducer are derived,[15]

$$\begin{aligned}&Z_P Z_0\cos(k_p n l_p)[c\tan(k_0 l_0)-\tan(k_h l_h)]\\&-Z_p^2\sin(k_p n l_p)-Z_h Z_0\tan(k_h l_h)\\&\cdot c\tan(k_0 l_0)\sin(k_p n l_p)=0, \qquad (1)\\&\omega n C_0-\alpha^2\{\sin(k_p n l_p)[2Z_P\tan(k_p n l_p/2)\\&+Z_h\tan(k_h l_h)]-Z_0 c\tan(k_0 l_0)\}\\&\cdot\{Z_P Z_0\cos(k_p n l_p)[c\tan(k_0 l_0)\\&-\tan(k_h l_h)]-Z_p^2\sin(k_p n l_p)\\&-Z_h Z_0\tan(k_h l_h)c\tan(k_0 l_0)\sin(k_p n l_p)\}^{-1}=0, (2)\end{aligned}$$

where Z_p, Z_0 and Z_h are characteristic impedances of piezoelectric stack, middle mass and radiation mass, respectively, α is the electromechanical conversion factor, and C_0 is the static capacitance of each piezoelectric wafer.

According to Eqs. (1) and (2), the resonance frequency f_r and anti-resonance frequency f_a can be calculated with the known geometrical parameters. In addition, the effective electromechanical coupling coefficient k_{eff} can be calculated approximately.

Optimized design of the transducer is conducted by using the FEM method. The impact of the length and location of the piezoelectric stacks on f_r and k_{eff} is studied and analyzed.

Suppose that the position of the piezoelectric stack shifts along the length-direction with a constant length. Figure 2 shows the piezoelectric location dependence of f_r and k_{eff} of the transducer.

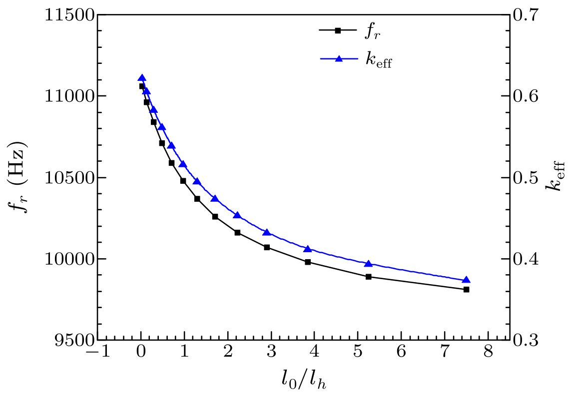

Fig. 2. Piezoelectric location dependance of f_r and k_{eff}.

As the piezoelectric stack moves to both the ends, l_0 increases and l_h decreases. Significant decreases of f_r and k_{eff} with increasing l_0/l_h are observed. Higher transmitting performance is obtained when the piezoelectric stacks are near the center of the transducer.

Assuming that the distance of piezoelectric ceramic and center plane is fixed, as the piezoelectric stacks become longer, the radiation mass is smaller. The ratio L_p/l_h increased with longer piezoelectric stacks. The curves of f_r and k_{eff} with respect to L_p/l_h are shown in Fig. 3.

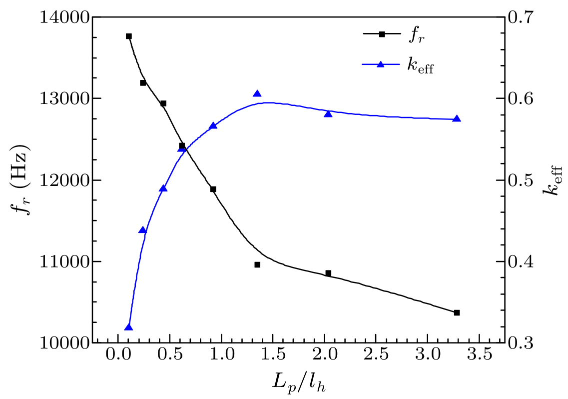

Fig. 3. Piezoelectric stack length dependance of f_r and k_{eff}.

With increasing L_p/l_h, f_r decreases and k_{eff} initially increases rapidly, and then declines gradually until the value of L_p/l_h becomes 1.5. The decrease of resonance frequency is due to the lower effective velocity. The increase of k_{eff} is due to the increase of C_0 with increasing L_p.

Based on our simulation, when the location of piezoelectric stack is near the center, and the piezoelectric stack is equal to 1.5 times the radiation mass length, the transducer has optimal transmitting performance. To verify the numerical results, two transducer models are prepared. Model 1 is the original transducer given by Cong *et al.*,[17] while model 2 is our optimized transducer. Detailed structural parameters are listed in Table 1.

Table 1. Structural parameters of two transducer models.

Transducers	l_0 (mm)	L_p (mm)	l_h (mm)	R_1 (mm)	R_2 (mm)
Model 1[17]	15	24	53.5	12.5	15
Model 2	0	57	28	12.5	15

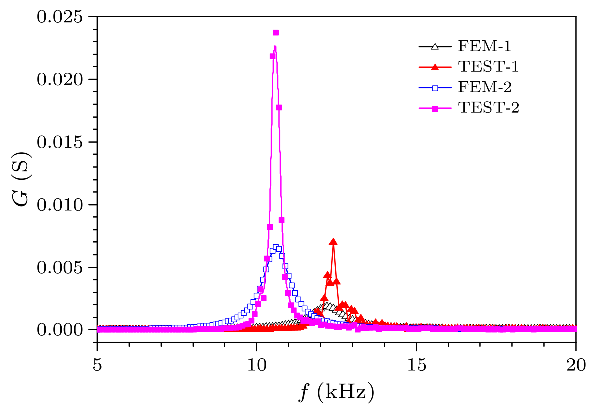

Fig. 4. Conductance curves of models 1 and 2 by FEM calculation and test.

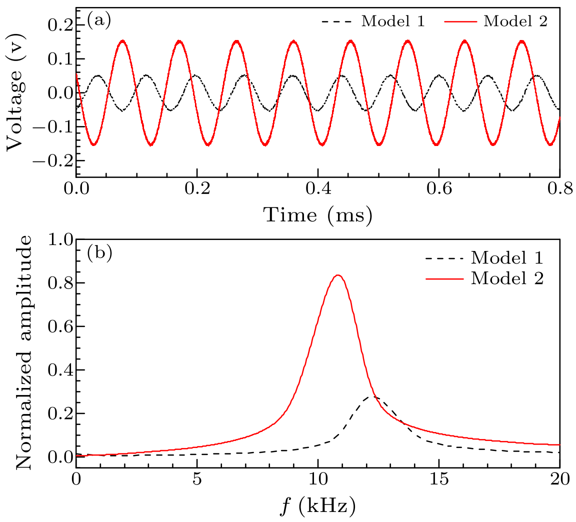

Fig. 5. Model borehole experimental results obtained for two transducers: (a) received waveforms and (b) frequency responses.

Admittance curves are tested in silicon oil by using the impedance analyzer (Agilent 4294 A). Figure 4 shows the conductance curves of models 1 and 2 by FEM calculation, as well as the test results. The solid and hollow lines represent tested and calculated data, respectively.

From Fig. 4 it is known that the resonance frequency of model 2 is lower than that of model 1. The FEM resonance frequencies are in good agreement with that of the tested result. Compared with the FEM results, the peak values of tested conductance are lower due to different settings of damping coefficients.

With the help of the optimizations, the experimental transducer samples are made and tested in a silicon-oil-filled semi-opened cylindrical aluminum pipe with its diameter of 0.15 m, and length of 2.0 m, respectively. Two sample transducers and a standard receiver are dipped in the pipe with an offset of 1.2 m. A sinusoidal voltage signal with a fixed amplitude is used to drive the two transducers. Received waveforms and the corresponding frequency response curves are shown in Figs. 5(a) and 5(b), respectively. It is apparent that the acoustic signal amplitude of the modified transducer (model 2) is about three times that of the original one (model 1).

In summary, by numerical analyses of influencing factors on transmitting performance, it is pointed out that higher performance of the transducer is obtained with suitable length of piezoelectric stack located near the center of the bar. The optimized transducer behaves at three times the amplitude of the original one. This work provides a theoretical and experimental basis for transmitter designing in acoustic logging, especially in acoustic logging while drilling.

We would like to thank Dr. Dai Yuyu in the Institute of Acoustics, Chinese Academy of Sciences, for technical help and discussion. Thanks also go to Liu Bin in the same institution for his help in experimental measurements.

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