Pulse width research on half-sine excitation signal for bending vibrator

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Abstract
Acoustic well logging adopts bending vibrators to transform high-voltage electric signals into acoustic signals. Excited acoustic signals have been proven best when the pulse widths are $0.5/f_0$ ($f_0$ refers to the resonance frequencies of the bending vibrator). However, acoustic logging uses transformers to improve the excitation power, and these transformers change the rectangular excitation signals into similar half-sine signals. We study the relationships between the pulse widths of the similar half-sine excitation signals and the characteristics of the excited acoustic signals. Finite element analyses are performed to investigate the displacements of the center node on the surface of the piezoelectric ceramics that are excited by the pulse signals of different widths. Then, we design a circuit to realise the rectangular and half-sine excitation signals. Subsequently, acoustic experiments are carried out in our sound-deadening water tank to certify the simulation results. Results indicate that the best pulse width is $0.75/f_0$.

Keywords: bending vibrator, pulse width, excitation signal, acoustic logging, finite element simulation

1. Introduction
Acoustic well logging tools play an important role in detecting the lithology and porosity of underground formation that are used for oil and gas exploration and exploitation (Lu et al. 2014; Wang et al. 2015; Lu et al. 2017; Li et al. 2020). Among these tools, bending vibrators are adopted for transformations between electric energy and sonic energy (Zhang et al. 2017b). This kind of bending vibrator is composed of one rectangular tabular metal substrate holder and two pieces of rectangular tabular piezoelectric ceramics (figure 1). Piezoelectric ceramics are bonded on the two sides of the metal substrate holder, and the polarisation orientation is along the height orientation and parallel to the $z$-axis. The metal substrate holder is much longer than the piezoelectric ceramics, allowing the bending vibrator to be electrically connected and physically fixed. Excited by electronic pulses, the piezoelectric ceramic on one side undergoes extension, while the other side undergoes contraction. Thus, the bending vibrator obtains bending oscillation and emits acoustic waves.

During acoustic well logging, the power of the acoustic signal excited by the bending vibrators should be as large as possible to improve the detection range. Meanwhile, the 3-dB bandwidths should be as narrow as possible to realise the best signal-to-noise ratio (Zhang et al. 2021). These characteristics of the emitted sonic waves determine the working performance of the logging tools. Meanwhile, these characteristics are collectively determined by the bending vibrators and their excitation circuits. Thus, many studies have been conducted on the relationships between the operational performances of the bending vibrators and the pulse widths of their excitation signals (Bera et al. 2010; Svilainis et al. 2015; Deng et al. 2020; Onykiienko et al. 2020; Botero & Alunno...
Most research is focused on rectangular pulse signals, and vibrators have been universally acknowledged to obtain the largest power when the pulse widths of their excitation signals are $0.5/f_0$ ($f_0$ refers to the resonance frequency of the bending vibrator) (Fa et al. 1996; Francek et al. 2019).

However, the excitation circuits of acoustic well logging tools usually use transformers to achieve a high voltage of thousand volts (Lu et al. 2017). These transformers that can be partly regarded as filters change the rectangular excitation signals into similar half-sine signals (Wang et al. 2017). Meanwhile, sine excitation signals have been researched and proven capable of obtaining excellent frequency characteristics (Tan et al. 2018). Unlike those of the rectangular signals, the relationships between the pulse widths of the similar half-sine excitation signals and the emitted acoustic signals have not been obtained. This research aims to study the relationships through simulations and experiments. In 2017, we introduced a high-voltage rectangular excitation method without transformers (Zhang et al. 2017a). In 2018, we designed a kind of excitation circuit to realise sinewave pulse signals on the basis of push–pull amplification technology (Tan et al. 2018). In this work, we first perform finite element analysis to obtain these relationships. Second, on the basis of aforementioned circuits, we design a circuit to realise the rectangular and half-sine vibrator excitation signals in the same circuit. Last, acoustic experiments are conducted in our sound-deadening water tank with the new excitation circuit.

2. Finite element simulation

Transient kinetic analysis was performed to obtain the transducer transient time and the frequency domain response characters (Kim & Kim 2009; Masmoudi et al. 2009; Narayanan & Schwartz 2010; Yaacob et al. 2011; Wu et al. 2012). Finite element analysis models were built in the ANSYS software. Three methods are usually adopted in transient kinetic analysis while executing the ANSYS software, namely, the full, reduced, and mode superposition methods. In this paper, the full method is used for the example analysis, while a sparse matrix solver is selected to obtain the solution. By analysing harmonic responses, the first order bending vibration can be excited along the length of the transducer, which is encouraged by the electronic signal of certain amplitude and frequency. Hence, the first mode bending vibration (hereafter referred to as the ground state) is studied in this paper. The material for the metal substrate holder was 45# steel whose length, width and thickness were 24, 9 and 1 mm, respectively. The material of the piezoelectric ceramic was PZT-8 whose length, width and thickness were 12, 9 and 1 mm, respectively. The density, Poisson ratio and Young’s modulus of the metal substrate holder were 7800 kg/m$^3$, 0.28 and $2.16 \times 10^{10}$ N/m$^2$, respectively. The essential parameters for the piezoelectric ceramic namely, the rigidity matrix $[c]$, the piezoelectric coefficient matrix $[e]$ and the dielectric coefficient matrix $[\varepsilon]$, are expressed as follows:

$$[c] = \begin{bmatrix} 14.688 & 8.109 & 8.105 \\ 8.105 & 13.171 & 3.289 \\ 3.289 & 3.135 & 3.135 \end{bmatrix} \times 10^{10} \text{N/m}^2,$$

(1)

$$[e] = \begin{bmatrix} 0 & 0 & -3.8754 \\ 0 & 0 & -3.8754 \\ 0 & 13.911 & 0 \\ 0 & 0 & 10.345 \\ 10.345 & 0 & 0 \end{bmatrix} \times N/V \cdot m,$$

(2)

$$[\varepsilon] = \varepsilon_0 \begin{bmatrix} 904.26 & 904.26 \\ 904.26 & 561.38 \end{bmatrix} = \begin{bmatrix} 7.99 \\ 7.99 \\ 4.96 \end{bmatrix} \times 10^{-9} \text{C/m}.$$

(3)

The time and frequency domain equations of the rectangular pulse signal whose duration and pulse width are
denoted as $t_0$ and $\tau$ as are follows:

$$U(t) = \begin{cases} U_0 \left( t_0 \leq t \leq t_0 + \tau \right), & \text{if } t \leq t_0 + 2\tau, \\ 0, & \text{otherwise}, \end{cases}$$

where $U_0$ (V) is the amplitude of the excitation signal. The following pulse widths are selected: 0.1$/f_0$, 0.25$/f_0$, 0.5$/f_0$, 0.75$/f_0$, 1.0$/f_0$, and 5.0$/f_0$ ($f_0$ is the ground state resonance frequency of the bending vibrator and 18.2 kHz for the fixed-boundary air condition). Meanwhile, the bending vibrator was in the fixed-boundary condition. Therefore, displacement constraints ($U_X = 0$, $U_Y = 0$ and $U_Z = 0$) were added to the nodes of $X = \pm 9$ mm along the length of the metal substrate holder.

The time and frequency domain equations of the half-sine pulse signal are as follows:

$$U(t) = \begin{cases} U_0 \sin \frac{\pi(t-t_0)}{\tau} & \left( t_0 \leq t \leq t_0 + \tau \right), \\ 0 & \left( t > t_0 + \tau \right), \end{cases}$$

$$U(\omega) = \frac{U_0}{j\omega} \left( 1 - e^{-j\omega\tau} \right),$$

where the duration, maximum voltage and pulse width of this signal are $t_0$, $U_0$ and $\tau$, respectively. $U_0$ (V) is the amplitude of the excitation signal. The following pulse widths were selected for the simulations: 0.1$/f_0$, 0.25$/f_0$, 0.5$/f_0$, 0.75$/f_0$ and 1.0$/f_0$, where $f_0$ is the resonance frequency of the bending vibrator. Meanwhile, the bending vibrator was in the fixed-boundary condition. Therefore, displacement constraints ($U_X = 0$, $U_Y = 0$ and $U_Z = 0$) were added to the nodes of $X = \pm 9$ mm along the length of the metal substrate holder.

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The time-domain normal displacement diagrams (a) and the corresponding spectral distribution diagrams (b) for the center node on the surface of the piezoelectric ceramics are shown in figure 2. The vibrator is excited by rectangular voltage signals of different widths. Thus, the normal displacement amplitude and the corresponding spectral amplitude are largest when the pulse width is 0.5$/f_0$. Meanwhile, the wave obtains the narrowest 3-dB bandwidths because the subsequent waves come after the first wave peak excited by the rising edge and the subsequent waves excited by the falling edge are added by the same phase when their widths are 0.5$/f_0$. In contrast, the two subsequent waves are added by different phases when their widths are not 0.5$/f_0$. That is, the normal displacement amplitudes on the surface of the bending vibrators and the emitted energies are largest and the electromechanical conversion efficiencies are highest when the widths of the rectangular signals are 0.5$/f_0$.

The time-domain normal displacement diagrams (figure 3a) and the corresponding spectral distribution diagrams (figure 3b) for the center node on the surface of the piezoelectric ceramics are shown in figure 3. The vibrator is excited by half-sine electric signals of different widths. Thus, the normal displacement amplitude and its corresponding spectral amplitude are the largest when the pulse width of the rectangular signal is 0.75$/f_0$. Furthermore, the waves obtain the narrowest 3-dB bandwidths at this time. That is, the normal displacement amplitude on the surface of the bending vibrator and the emitted energy are the largest and the electromechanical conversion efficiencies are the highest when the width of the half-sine signals is 0.75$/f_0$, unlike those of the rectangular voltage signals.

These figures show that the normal displacement amplitudes are the largest when the pulse widths are 0.5$/f_0$ for the rectangular voltage signals and 0.75$/f_0$ for the half-sine voltage signals. Figure 4 presents the time-domain normal displacement comparison diagrams (figure 4a) and the corresponding spectral distribution comparison diagrams (figure b) that are excited by the rectangular and half-sine voltage signals of the best widths. The normal displacement amplitudes and the corresponding spectral amplitudes of
the rectangular signals are larger than those of the half-sine signals because when all the other conditions are the same, the input power of the rectangular signals for the bending vibrators is the largest among the other signals. This conclusion is consistent with that of our earlier studies. In our earlier research, we found that the sound pressures of the acoustic signals emitted by rectangular excitation signals are much bigger than those of the acoustic signals emitted by the half-sine excitation signals, while other conditions remained unchanged (Zhang et al. 2017a).

3. Acoustic experiments

3.1. Design of excitation circuit

Acoustic experiments were designed to certify the simulation endings. To avoid irrelevant detrimental effects, the same bending vibrator was excited by the same circuit, producing the rectangular and half-sine signals of different widths. Thus, we designed a new excitation circuit to obtain rectangular and half-sine excitation signals for the bending vibrators. Figure 5 shows that the excitation circuit consisted of a transmitting controller, a signal generator, a rectifier circuit, a power amplifier, a high-voltage power supply circuits, a series of storage capacitors, a V-groove metal-oxide semiconductor (VMOSEFT) and its driver circuit. The transmitting controller was a DSP, a kind of high-speed digital signal processor. It collected control signals via the CAN bus, and these control signals were approximately about the amplitudes, the pulse widths and the phases of the excitation signals (Zhang et al. 2016). To obtain the half-sine signals, the DSP chip obtained the half-sine data stored in its FLASH storage (Zhang et al. 2014), and transferred these data into the signal generator to produce low voltage control signals. These control signals were adjusted by the rectifier circuit to change their amplitudes and frequencies. Thereafter, these signals were amplified by the power amplifier to improve their driving power and then by a transformer to thousands of volts. Last,
3.2. Acoustic experiments in the sound-deadening water tank

Acoustical experiments were carried out in our 6.0 × 6.0 × 6.0 m sound-deadening water tank (Zhang et al. 2021). The experiment system included the designed circuit, a fixed bending vibrator, a positioning control system, a broadband hydrophone and an oscilloscope (figure 6). The six planes of the water tank are filled with sound-deadening wedges (the blue materials), which can...
absorb more than 99% of acoustic signals. The vibrator is excited by the designed circuit and fixed on the first mechanical arm. This arm can realise precision position in three dimensions and circumferential space. The hydrophone is fixed on the second mechanical arm, which can only realise precision position in three dimensions. The material for the metal substrate holder of the vibrator was 45# steel whose length, width and thickness were 102, 25 and 1.6 mm, respectively. The material of the piezoelectric ceramic was PZT-8 whose length, width and thickness were 72, 25 and 1 mm, respectively. The boundary condition is a fixed-boundary silicon oil condition. The resonance frequencies of the bending vibrators were measured by an impedance analyser in advance, and the bending vibrator with a resonance frequency of 15.5 kHz was selected to be the transmitter. The hydrophone was accurately positioned by the positioning control system. According to the main workflow, the excitation circuit produced high-voltage electronic signals of different widths to

Figure 7. (a) The time-domain rectangular and (b) half-sinewave excitation signals of different widths excited by the excitation circuit.

Figure 8. The (a, c) time-domain and (b, d) frequency domain acoustic waves excited by (a, b) rectangular and (c, d) half-sinewave excitation signals of different widths.
excite the transducer. Meanwhile, synchronising signals were sent out to start the concurrent data acquisition of the oscilloscope. Afterward, the acoustic waves emitted by electronic signals of different shapes and widths were transmitted via the water and finally received by the hydrophone. Figure 7 presents the time-domain rectangular and half-sinewave excitation signals of different widths excited by the excitation circuit, indicating that the excitation circuit obtained the required excitation signals.

4. Discussion and conclusions

Like previous theoretical research endings, the experiment endings in this study illustrate that the emitted acoustic energies are the largest and the 3 dB bandwidths are the narrowest when the widths of the rectangular excitation voltage signal are $0.5/f_0$ ($f_0$ refers to the resonance frequency of the bending vibrator). However, when transformers are adopted, the rectangular signals change to similar half-sine signals. The simulation and experimental results proved that the best pulse width is $0.75/f_0$ (figure 8). Bending vibrators perform free vibrations when excited by the rectangular signals. These vibrations consist of the vibrations caused by the rising edge of the excitation signals and the falling edge. When the two vibratory displacements obtain the same phases, the amplitudes of the excited waves are added together, producing the maximum amplitude. Bending vibrators obtain forced vibrations when excited by the half-sine signals. However, theoretical explanations have not been researched and reported.

This paper discusses the similar half-sine signals caused by transformers. However, half-sine and sinewave signals can also be achieved by other methods, producing consistent conclusions. Meanwhile, most of the complicated excitation signals can be regarded as the combination of rectangular and sinewave signals, and this study may be beneficial to these signals. Additionally, although this study focused on the bending vibrators of acoustic logging, it is of significance to transducers of other shapes and in other domains.

Considerable attention should be given to the impedance matching between the excitation circuit and the transmitting transducers in the acoustic experiments because poor impedance matching may lead to incorrect experiment endings.

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