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A general experimental system for the development of acoustic logging tools

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ABSTRACT

Laboratory testing is a pre-requisite for the practical application of new methods and techniques, and it is crucial in the research and development of acoustic well-logging tools. Various tools have been developed based on different acoustic logging theories and methods. Thus, these tools are equipped with different acoustic sonde structures. To meet the test requirements of different tools in a laboratory environment, we designed a general experimental system that includes hardware platform, software platform, and model wells according to the common structure of actual logging tools. Similar to the internal electrical structure of downhole tools, the hardware platform consists of several main parts, such as power supply, control and telemetering, acoustic emission, and data acquisition. The functions of this hardware platform include controlling the working sequence of the experiment, exciting the transmitter sonde, and collecting the acoustic signals received by the receiver sonde. The software platform installed in the host computer provides a human–computer interface for the experimental system to complete the data transmission between the host computer and the hardware platform, store measured data, and process the data in real time. The model wells approximate the actual engineering environment and stratum condition for system testing. A series of practical laboratory experiments is conducted in the model wells by using this experimental system. The process proves that the hardware and software of the experimental system can work in coordination, and the experimental system meets the basic testing requirements of conventional acoustic logging tools.

I. INTRODUCTION

In oil–gas exploration and development, acoustic logging is a geophysical method to obtain the geological parameters of underground reservoirs by measuring the acoustic characteristics of rocks.[1–3] Acoustic logging tools based on various logging theories are developed for underground information capture and signal processing.

An engineering schematic of conventional cable logging is shown in Fig. 1. The ground system and cable winch are mounted on an engineering vehicle located on the ground. The ground system is utilized in engineering monitoring, parameter setting, and data processing. The cable winch drags the downhole tool with a special armoured cable and supplies power to the tool. As shown in Fig. 2, the main components of the downhole tool are the transmitter sonde, receiver sonde, and isolator.[4,5] Both the transmitter and receiver sondes are composed of acoustic transducers, and the function of the sondes is to emit acoustic pulses and receive echo signals, respectively. The downhole tool starts the logging operation after receiving the start-up command issued by the ground system through the cable. First, the electronic system of the tool controls the transmitter sonde and makes it emit acoustic pulses into the target strata. Second, the receiver sonde detects and collects acoustic signals that carry the strata information after propagation. Finally, the downhole tool uploads the collected signals to the ground system through the cable for processing and analysis.

In addition, the acoustic signal that propagates along the tool housing is strong but usually considered useless; hence, the direct wave (tool mode signal) must be attenuated to avoid its effect on the detection of informative strata signals. During the process, the isolator prevents the direct signal coupling between the transmitter and the receiver sondes.[6,7] Thus, the isolator is a dispensable part of the acoustic logging tool.

Theoretical research, structure design, sonde testing, tool assembly, and field testing are the basic development processes of acoustic logging tools. Tool testing in a laboratory environment is

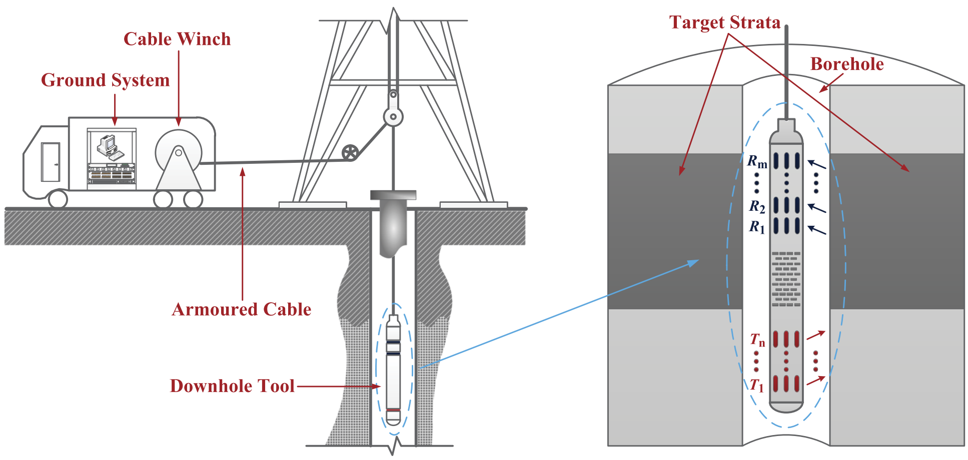

FIG. 1. Sketch of conventional cable logging engineering.

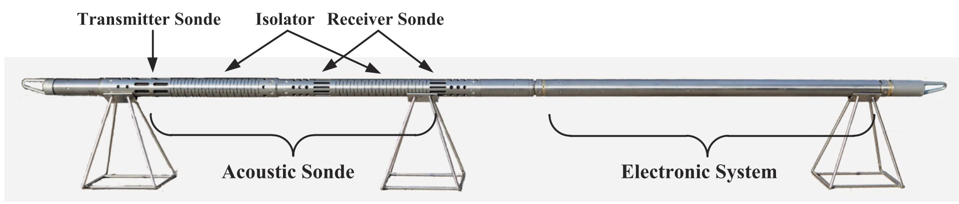

FIG. 2. Mechanical structure of a conventional acoustic logging tool.

crucial because it provides a preliminary verification of the method validity and offers practical guidance for the hardware and software design of the actual tool. The structure and performance of the acoustic sonde largely determine the overall functionality of the entire tool. Hence, acoustic sonde design is the premise of electronic system, software, and mechanical design.

The traditional testing method is to design a specific test–bench according to the characteristics of the tool itself. However, various tools are equipped with different acoustic sondes. Due to the lack of versatility and generality of the specific test–benches, the efficiency of sonde testing is relatively low, which also delays the development of new tools. Thus, according to the common structure of various acoustic sondes, we designed a general experimental system that can meet the test requirements of conventional acoustic logging tools. This system is composed of hardware and software platforms, and model wells. The main parts of the experimental system are discussed separately in Secs. II and III.

II. HARDWARE PLATFORM DESIGN

The hardware platform of the experimental system should perform tool control, acoustic pulse emission, and signal acquisition to simulate the electronic system of actual downhole tools.[8–10] As shown in Fig. 3, the basic parts of the hardware platform are the

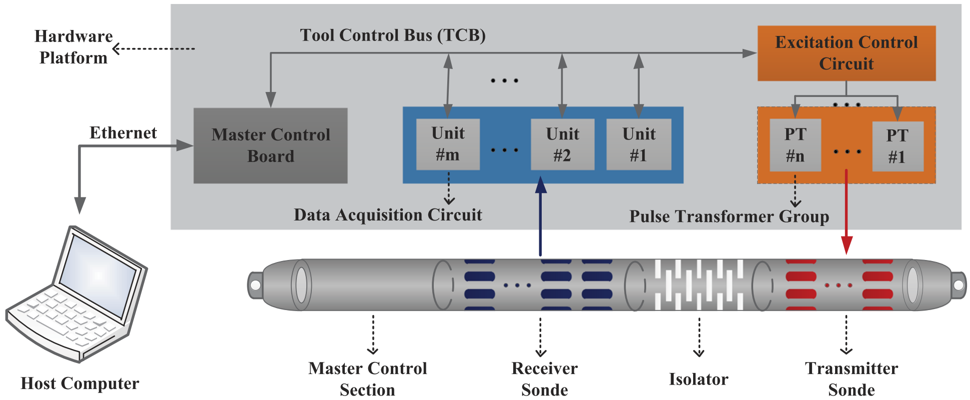

FIG. 3. Structure of the acoustic sonde and hardware platform.

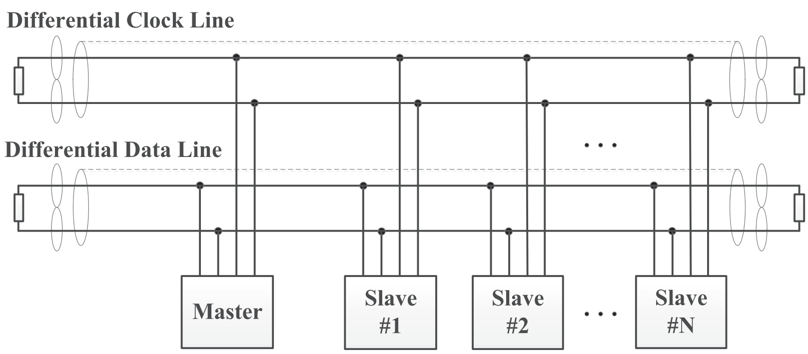

FIG. 4. Physical structure of TCB. In this hardware platform, the master control board acts as the master node, and the excitation control circuit along with each unit of the data acquisition circuit acts as the slave nodes. The master node drives the clock lines to provide a reference clock for each slave node, and all nodes send or receive data according to the reference clock.

master control board for realizing tool control and data transmission, an excitation control circuit and pulse transformer group for realizing acoustic pulse excitation, and a data acquisition circuit for realizing acoustic signal acquisition.[11,12] Ethernet is used to connect the hardware platform to the host computer, and the parts in the hardware platform are connected by the tool control bus (TCB).

When the experimental system operates, the host computer sends the working parameters and control commands to the master control board of the hardware platform through Ethernet. The master control board decodes the commands of the host computer, notifies the excitation control circuit through TCB to generate high-voltage excitation pulses, and sends the acquisition synchronous signal to the data acquisition circuit. The master control board polls the status of all data acquisition units through TCB until the data acquisition is completed.

A. Tool control bus

TCB is a self-defined serial data bus, and it works in the half-duplex synchronous transmission mode with an effective data transmission rate of 20 Mbps. As shown in Fig. 4, the bus consists of a master node, several slave nodes, a pair of differential data lines, and a pair of differential clock lines.[13,14] Communication notes can be added to the hardware platform with the bus structure, and this condition is conducive to hardware expansion and system upgrade.

B. Master control board

The circuit structure of the master control board is shown in Fig. 5. The digital signal processor (DSP) and field-programmable gate array (FPGA) are the core components of the circuit,[15,16] and they can control the system's working sequence, communication, and data storage. In logging engineering, the data exchange between logging tools and the telemetry system, which is responsible for cable communication, is usually realized by the controller area network (CAN). Hence, the master control board retains the CAN communication function to simulate the electronic system of actual logging tools. In addition, industrial personal computers (IPCs) generally do not have a CAN interface. Therefore, to realize data exchange between the host computer and the hardware platform, a telemetry module with the function of CAN–Ethernet conversion is designed and integrated into the master control board. $FPGA_1$ is the

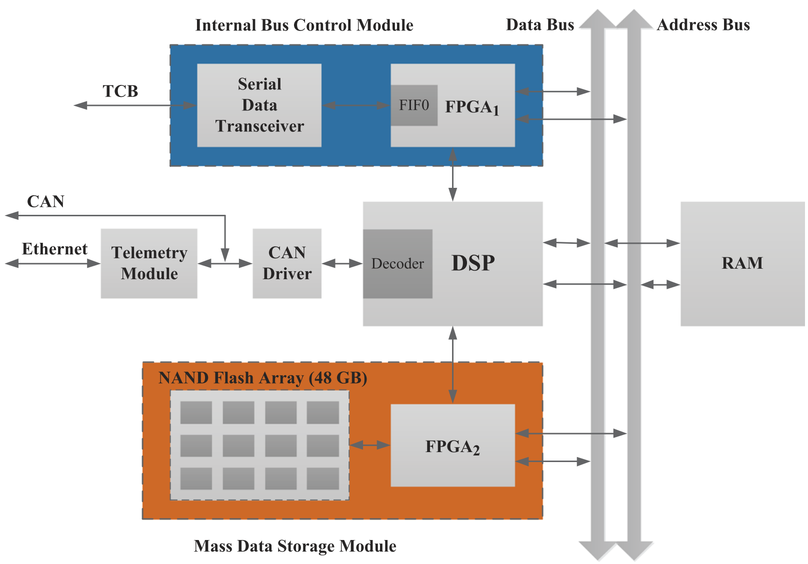

FIG. 5. Structure of the master control board.

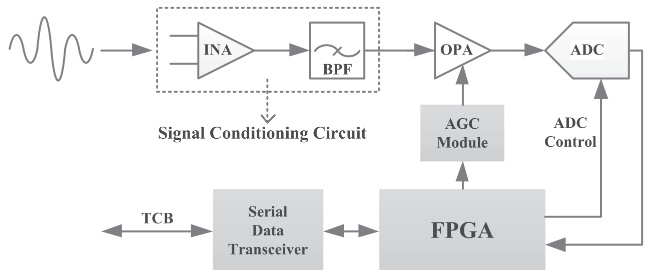

FIG. 6. Circuit diagram of the data acquisition unit. As the master controller of the unit, FPGA performs command decoding, data uploading, analog–digital conversion (ADC) control, and automatic gain control (AGC). INA represents the instrumentation amplifier, BPF represents the bandpass filter, and OPA represents the operational amplifier.

main controller of TCB, and it generates synchronous clocks and transmits bus data by controlling the serial data transceiver according to the instruction of DSP. With the development of logging techniques, the amount of collected data increases continuously, and the data measured by many logging tools cannot be uploaded to the ground system in real time because of the limited data transmission rate. Thus, more and more logging tools with the function of downhole data storage have been developed. To deal with this situation, a mass data storage module is added to the circuit to meet the test requirements of these tools. In this module, $FPGA_2$ and a NAND flash array act as the storage controller and storage medium, respectively.[17–19] A high-reliability embedded file management system with functions of error checking and correction (ECC) checking, bad block management, and wear leveling management is built in $FPGA_2$. The file management system can write, read, and erase the flash memory under DSP instruction.

C. Data acquisition circuit

The receiver sonde of conventional acoustic logging tools is usually composed of several receiving stations, and each station collects multi-channel acoustic signals that correspond to its location. During analog signal acquisition, the acquisition circuit should be located as close as possible to the sensor (acoustic transducer) to minimize the electromagnetic interference (EMI) noise. Therefore, the data acquisition circuit of acoustic logging tools is usually composed of several acquisition units, and each unit is responsible for collecting the acoustic signals of the corresponding receiving station. To simulate the electrical structure of actual downhole tools, the data acquisition circuit of the hardware platform is also composed of several independent acquisition units, a circuit diagram of the unit is shown in Fig. 6. At the end of a working cycle, the master control board sends an uploading command to each acquisition unit by polling, and each unit uploads the collected acoustic data of its corresponding receiving station through the TCB bus.

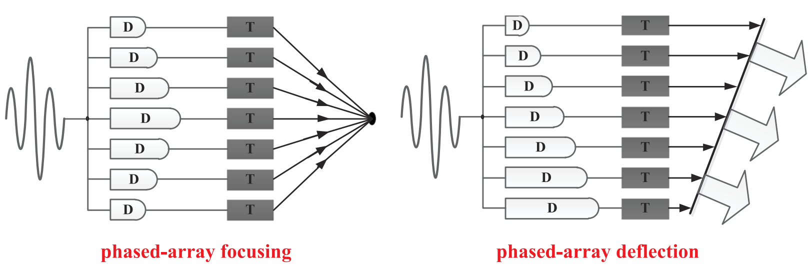

FIG. 7. Schematic of acoustic phase-controlled emission. D represents delay control, and T represents the acoustic transducer.

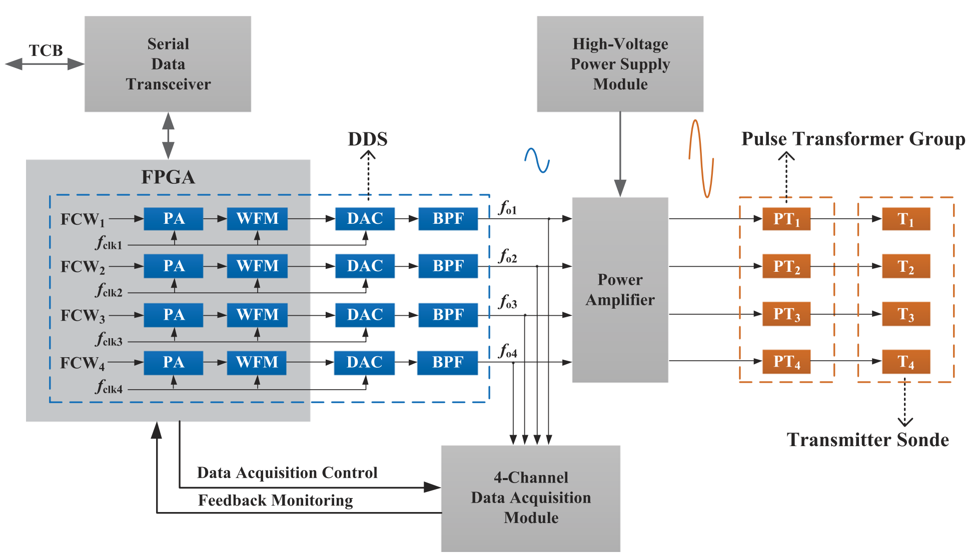

FIG. 8. Diagram of the multi-channel arbitrary waveform excitation control circuit. This circuit has four independent DDS modules, and each DDS module consists of a phase accumulator (PA), waveform memory (WFM), digital–analog converter (DAC), and bandpass filter (BPF). PA and WFM are generated inside FPGA. PA generates circular addresses for phase lookup. WFM is implemented by the internal ROM of the FPGA, which stores the phase-amplitude tables of arbitrary waveforms. In addition, a four-channel data acquisition module is introduced into the excitation control circuit to observe the excitation signals generated by DDSs.

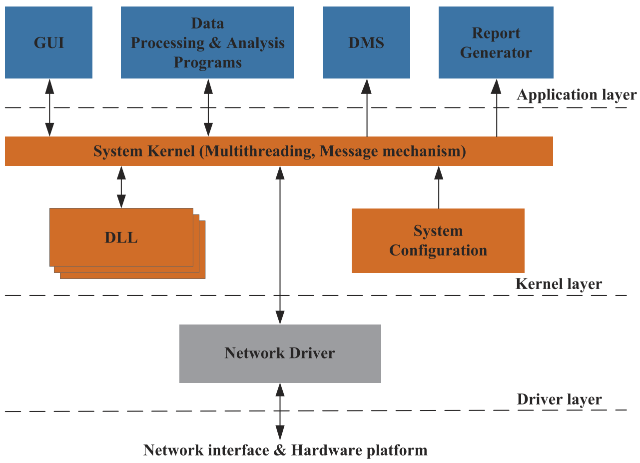

FIG. 9. Architecture of the software platform.

D. Excitation control circuit

Phase-controlled emission is a technique for acoustic beam scanning, focusing, and deflection that uses an acoustic transducer array. With the development of acoustic logging technology, an acoustic phased array has been gradually applied to acoustic logging tools. As shown in Fig. 7, the transducers in the transmitter sonde can form a simple one-dimensional linear array. According to the principle of phase-controlled emission, acoustic beam focusing and deflection can be realized by reasonably controlling the excitation delay applied to each array element.[20–22]

To enable phase-controlled emission of the transmitter sonde, we design a multi-channel excitation control circuit with the function of arbitrary waveform generation. Control of phase delay and pulse amplitude are keys in realizing phase-controlled emission. Hence, the excitation control circuit uses the direct digital synthesizers (DDSs) to generate arbitrary excitation signals.[23,24] As shown in Fig. 8, high-voltage excitation is realized by coordinating the DDS modules with the power amplifier and pulse transformers.

The process of DDS waveform generation can be regarded as the inverse process of signal acquisition. First, under the control of system clock (f_{clk}) and frequency control word (FCW) generated by the FPGA, waveform memory (WFM) outputs the corresponding digital waveform amplitude by cycle according to the phase address of the phase accumulator (PA). Then, the digital–analog converter (DAC) converts the digital amplitude to the analog waveform. Finally, the desired low-voltage excitation signal is generated after bandpass filtering. If the bit width of the digital waveform is N, and the FCW is K, then the frequency of the output signal is

$$f_o = \frac{K}{2^N} f_{clk}. \tag{1}$$

Equation (1) shows that the frequency of the output waveform can be adjusted by changing f_{clk} and FCW.

III. SOFTWARE PLATFORM DESIGN

In conventional logging engineering, the ground system mounted on the engineering vehicle is usually connected to various downhole tools for operation monitoring, working parameter setting, file storage, and real-time data processing and analysis. The software platform of the experimental system is used to simulate the ground system in actual logging engineering.

The Windows kernel based software platform is installed in the host computer. As shown in Fig. 9, the software platform consists of an application layer, kernel layer, and driver layer. The application layer is at the top of the software architecture and interacts directly with users. In this layer, several function modules play their respective roles. The graphical user interface (GUI) is used for parameter setting, data visualization, and operation monitoring. The functions

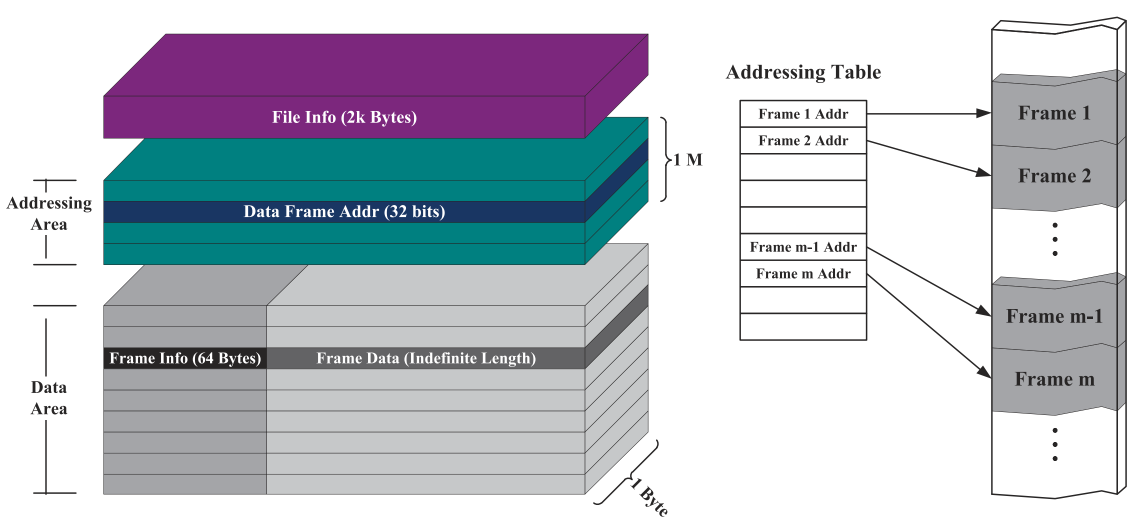

FIG. 10. Format of the standard file and relationship of address mapping.

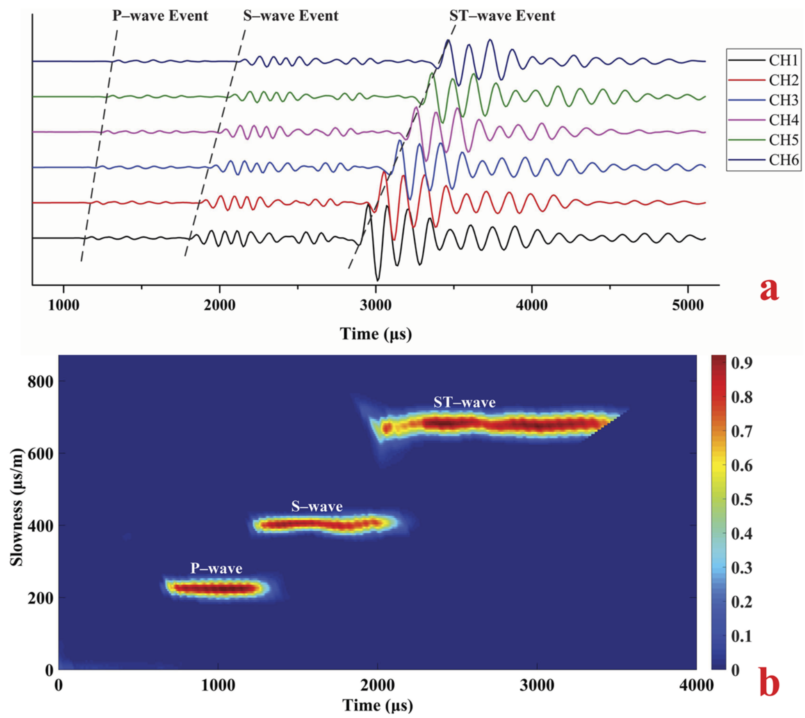

FIG. 11. (a) Acoustic waveforms measured by the acoustic sonde, showing the arrivals of the P–wave, S–wave, and ST–wave according to wave velocity and chronological order, and (b) application effect of the STC method, showing the cross-correlation coefficient of the several wave modes appear in the multi-channel signals.

of the report generator are to record experiment information and generate experiment reports. The document management system (DMS), and data processing and analysis programs are introduced separately in Secs. III A and III B.

A. Document management system

DMS is responsible for data formatting and storage management. In practical engineering, downhole tools send collected data to the ground system in the form of data packets. All data packets uploaded in the process are recorded in raw files. Standardized processing tasks, such as useless information elimination, data sorting, and waveform splicing, are necessary to facilitate the graphical display and data processing. As shown in Fig. 10, the format of a standard file is defined to store the processed data, and each file is composed of the file information section, addressing area section, and data area section. The file information section records tool information, test information, stratum depth, check words, and so on. The data area section stores the frame information and frame data; the former records the working parameter configurations and check words of data, and the latter records all the data obtained during this working cycle. To facilitate random reading of data, the addressing table that records the addresses of all data frames is stored in the addressing area of the file.

B. Data processing and analysis programs

Data processing and analysis programs run in the background of the software platform. One of the most important tasks in the data processing of acoustic logging is to obtain the acoustic slowness (interval transit time) of the multi-mode waveforms. According to the calculations of slowness inversion, analysts can retrieve the desired geological parameters of the target strata. The commonly used methods to obtain acoustic slowness are threshold detection and slowness-time coherence (STC).[25–27] The former has a simple algorithm and high processing speed, but the method is sensitive to noise jamming and has relatively poor accuracy.

FIG. 12. (a) Picture of the model well group and (b) scene of an acoustic sonde experiment.

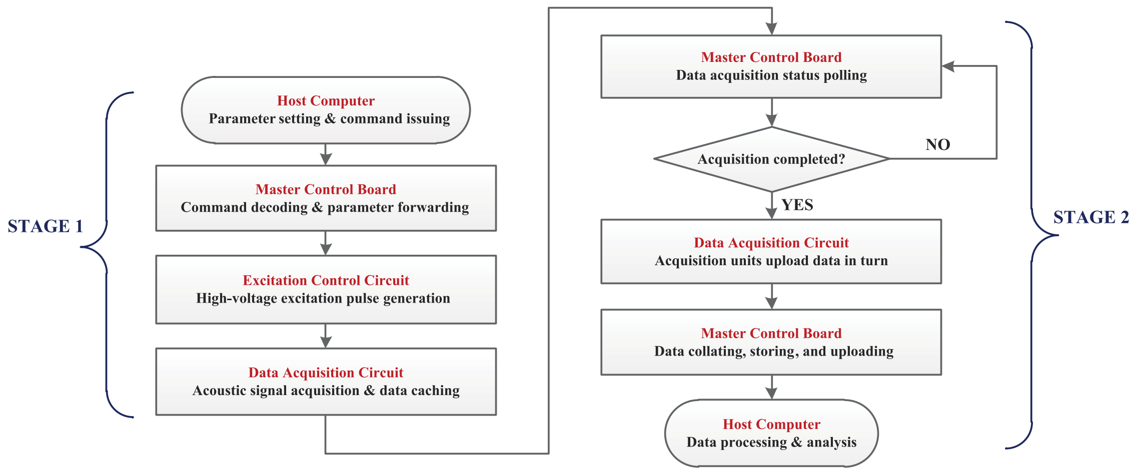

FIG. 13. Flowchart of a single working cycle. Each cycle can be divided into 2 stages: Stage 1 is for working parameter setting, command issuing, and transmitter sonde excitation and stage 2 is for waveform acquisition, data uploading, and processing.

Compared with threshold detection, the STC method obtains acoustic slowness by calculating the correlation between measured acoustic waveforms, which endows the method high accuracy. Therefore, STC is adopted in the software platform for acoustic slowness calculation. The following are the basic principles of the STC method: regarding the acoustic waveform sequence as a two-dimensional mesh network of time and slowness, calculating the cross correlation of acoustic waveforms continuously in a certain time window T_w and searching the acoustic slowness at the maximum value of the cross-correlation function. Assuming that the receiver sonde of the tool obtains N channel waveforms, the distance between two receiving stations is d, and the time window is taken at time T; if a slowness value of s is selected within the slowness range, then the cross-correlation function of the N channel waveforms is defined as follows:

$$\rho(s,T) = \frac{\int_T^{T+T_w} \left|\sum_{m=1}^{N} X_m[t+s(m-1)d]\right|^2 dt}{N\int_T^{T+T_w} \sum_{m=1}^{N} |X_m[t+s(m-1)d]|^2 dt}. \quad (2)$$

A varying cross-correlation function curve can be obtained by sliding the position of T_w in the time interval continuously. Then, the acoustic slowness of a specific waveform phase can be obtained from the corresponding slowness s when the curve reaches its maximum value.

Figure 11 shows the measured waveforms of a cable tool and processing results of STC. The tool consists of a monopole source, six receivers, and a cutting groove isolator. The source spacing (the length between the transmitter and the nearest receiver) is 3658 mm, and the receiver spacing (the length between adjacent receivers) is 152 mm. The excitation frequency of the monopole source is 8 kHz, the sampling point number of a single channel waveform is 732, and the sampling interval is 12 μs. Acoustic waves generated by the monopole source propagate along a sand formation and that produce the P–wave, S–wave, and Stoneley wave (ST–wave). The processing results show the slowness and energy intensity of the multiple mode waves. It should be noted that the direct wave is severely attenuated and does not appear in the figure, owing to acoustic insulation of the isolator.

IV. SYSTEM TESTING AND APPLICATION

Field scenes of the model well group and an acoustic sonde experiment are shown in Fig. 12. The model well simulates an actual oil well; the host computer and the software platform installed in the computer simulate the ground system; the acoustic sonde to be

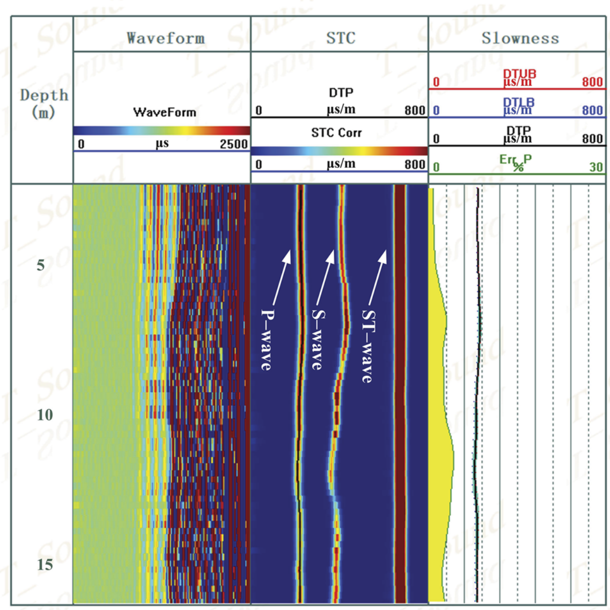

FIG. 14. Data processing effect graph of a depth section in the model well, results showing the measured waveform descriptions, cross-correlation coefficients of multi-mode waves, and P–wave slowness.

tested and the hardware platform simulate the actual downhole tool. In the experiment, the positioning system controls the hoister to pull the acoustic sonde in a model well and lift it at a uniform speed. The experimental system begins to operate and performs acoustic excitation and data acquisition with a fixed period, and the testing process of each period is called a working cycle (Fig. 13).

Measured data of different depth points can be obtained as the acoustic sonde moves in the model well; meanwhile, the data processing and analysis programs can calculate the acoustic slowness of the corresponding depth points. By recording the acoustic slowness of each depth point, the software can draw a slowness curve that changes with depth, as shown in Fig. 14. The slowness–depth curve is a vital resource for geological analysis. Geologists can estimate the acoustic properties of the target strata around the borehole and determine the desired geological parameters by slowness inversion.

V. CONCLUSION

Laboratory testing is crucial in the research and development of acoustic logging tools because it verifies the acoustic logging theory and identifies various engineering problems that may occur in the laboratory stage. Different tools are usually equipped with different acoustic sonde structures, thereby varying the task demands of acoustic sonde testing. Thus, a general experimental system that can be applied to the acoustic sonde testing of most conventional tools is helpful to the hardware and software design of actual tools and would remarkably improve the development of tools.

The hardware platform of the experimental system has several independent parts, and each part can be divided into several functional modules. All parts of the platform are connected by TCB which has good expansibility. The "building block" framework is conducive to expansion and upgrading, which makes the hardware platform usable for testing and development of various new tools. Similarly, the software architecture of the experimental system is designed based on the modular design concept and is thus helpful for system upgradation and function improvement when confronting new testing tasks. A format of the standard file is defined in DMS, which enables the software platform to manage the data files of various types of tools and endows the software with strong data compatibility. Several essential acoustic data processing methods, such as digital filtering, dispersion analysis, and STC calculation, are integrated into the data processing and analysis programs. With these methods, basic real-time processing of acoustic signals is possible.

A series of acoustic sonde tests is conducted in the model well to simulate the practical environment in logging engineering. The process proves that the hardware and software of the experimental system can work in coordination, and the final data processing results show that the experimental system meets the basic testing requirements of conventional acoustic logging tools.

ACKNOWLEDGMENTS

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