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A new downhole magnetic resonance imaging tool

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ABSTRACT

This paper presents a novel inside-out magnetic resonance imaging (MRI) device with axial, radial and circumferential measurements. The designed MRI probe employs array antenna and phase-controlled transmitters to accomplish spin echo data acquisition. Nuclear Magnetic Resonance (NMR) has been successfully applied to downhole formation evaluation with unique information of in-situ reservoir properties for decades. Traditional NMR logging measurements, however, are averaged the whole sensitive volume. The designed downhole MRI tool overcomes the weakness of traditional technique and raise new applications such as for heterogeneous formation evaluation around well bore and for harsh borehole conditions. We demonstrate the feasibility with a prototype in a calibration tank. The acquired echo trains from different direction and different radial depth are in good quality.

1. Introduction

Nuclear Magnetic Resonance (NMR) logging has been applied in the petroleum industry as a powerful geophysical prospecting technology for decades and is still under rapid development [1]. NMR logging measurements provide unique information on reservoir fluid properties, with which porosity, pore size, clay bound water, capillary bound water and free fluid, permeability, and hydrocarbon saturation and oil viscosity can be evaluated and estimated. Many bottleneck problems in oil and gas exploration are resolvable with NMR logging information, such as low-resistivity/low hydrocarbon saturation/low porosity/low permeability/complex lithology/special lithology/complex pore structure reservoirs.

The downhole NMR logging instrument detects hydrogen signals of pore fluids from a wellbore of thousands-meters under subsurface. Therefore, instrument size restrictions, harsh working environments (high temperature, high pressure) and tool motions etc. Make the tool design and implementation more difficulty than laboratory NMR. In 1960, Brown and Gamson designed the first NMR logging device using earth magnetic field [2–4]. In 1978, Jackson invented the NMR logging tool with inside-out permanent magnet [5]. This "inside-out" design has been the fundamental for NMR logging tool development after that time [5].

Different versions of NMR logging tools have been developed and used in the logging industry, of which two types of probe can be classified as "centralized-type" and "pad-type". The centralized-type probe is put in the center of borehole, and the measured signals are from cylindrical slices [6,7]and the pad-type probe is always contacted to the wellbore, and the measured signals are from un-directional radial slices [8–11]. Usually, the centralized-type probe provides higher signal to noise ratio than the pad-type probe, and the pad-type probe provides higher vertical resolution than centralized-type probe. Both centralized-type and pad-type probe provide measurements along with vertical-depth (cable lifting direction) and radial-depth from wellbore to formation, and are unable to distinguish the circumferential change of the wellbore.

Considering the heterogeneity of reservoirs, in both conventional and unconventional oil/gas, it is important to design an NMR logging tool to measure the azimuth properties of formation along wellbore. The new tool has been designed to achieve circumferential scanning measurements, and to identify and evaluate the heterogeneity of the logged formation and fluids.

2. Design of the downhole MRI tool

The new tool, downhole circumferential scanning MRI tool, consists of three components: probe, electronic cartridge, and capacity cartridge. The probe consists of magnet and antenna. The magnet is applied to produce static magnetic field for polarizing protons of pore fluids. The antenna is used to transmit radio frequency pulse and receive echo signals. The electronics is used for RF power transmitter, echo acquisition and other auxiliary controlling. The capacity cartridge

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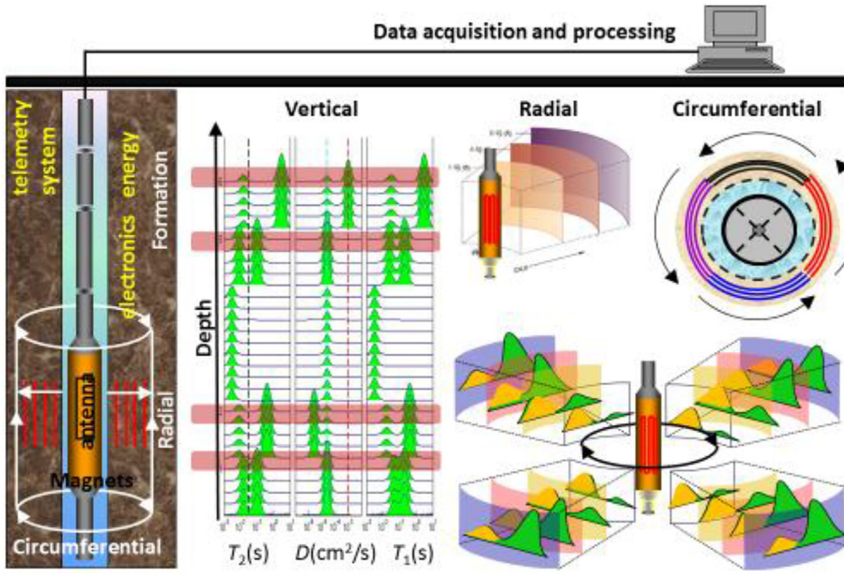

Fig. 1. Illustration of the three-dimensional downhole magnetic resonance logging tool.

supplies power to transmitter. Through the control of antenna and echo acquisition, the instrument can realize vertical, radial and circumferential NMR signal measurements, as shown in Fig. 1.

The goals of the designed MRI logging tool should include but not limit to below specifications:

- Logging speed: up to **16 ft/min**
- Depth of investigation: up to 10 **cm** from borehole wall
- Number of azimuth measurements: **4–16**
- Number of radial slices: up to **8**
- Porosity range: 0–100 **PU**
- Maximum probe radius: 15.5 **cm**
- Maximum temperature/pressure: 175 °**C**/140 **mPa**
- Each sector can be multi-points calibrated independently

2.1. Probe design

Probe is a critical component of NMR logging tool. The design of an NMR probe is an issue of electromagnetic fields and includes optimization of both structure and material [12,13]. A set of permanent magnets are used and well assembled to produce symmetric static gradient magnetic field B_0, and an array of antenna is employed to transmit RF pulse and to receive echo signal.

The magnet is designed based on classic "inside-out" concept [5]. To achieve NMR measurement with circumferential scanning, the static magnetic field is produced by multiple-unit permanent magnets that include two N poles opposite main magnets. The main magnets are composed of multi small magnets with axial polarization and a series of focusing magnets. Owing to well bore restrictions, the outer diameter of the probe should not exceed the borehole size. The main magnet is tubular with outer diameter of 13 cm, and inner diameter of 6.1 cm. The focusing magnets with Halbach structure were employed between main magnets to improve depth of investigation for easy excitation and mud signal elimination. The optimized static magnetic field distribution is shown in Fig. 2. From the above introduction, the static magnetic field contour is a circle in the range of detection. The magnetic field strength decreases with the increase of detection depth.

Array antenna is designed by using the straps for transmitting RF field and receiving echoes. The designed array antenna has 24 copper strips that equidistantly surround to the magnet. Different combination of the array antenna will come to different opening angles and different azimuth. When the number of stripes increase, the opening angles increase accordingly. Fig. 3 Is radio frequency field strength distribution of the designed array antenna.

The design of the magnet and array antenna achieve the resonance condition for B_0 and B_1 orthogonal matching, enhancement of signal to noise ratio, enlargement of sensitive volume, overall mechanical properties of the probe, and assembly process requirements. The designed tubular MRI probe can be flexibly arranged to either centralized- or pad-type measuring NMR signals with reasonable sensitive volumes by changing the configuration of array antenna.

2.2. Electronics design

Electronics setups control commands, creates pulse timing, and controls array antenna emitting RF pulses and receiving echo signals, and communicates with surface equipment which is usually on a track [14].

The designed electronics for the new MRI logging tool meets the requirement of array antenna high power RF pulses and very weak signal amplification at downhole high temperature and harsh environments. Electronic system consists of array antenna controller, transmitter and receiver, and main controller (digital). The functional block is shown in Fig. 4.

2.2.1. Digital main controller circuit

The main controller with embedded system architecture is based on digital signal processor (DSP) and field programmable gate array (FPGA). DSP is responsible for signal processing and the communication. FPGA achieves the entire timing control signals, pulse sequences, various observation modes and buffers digitized data after ADC sampling with the synchronous first in first out (FIFO) memory from inside embedded memory.

Fig. 5 is the functional block diagram of the main control system. The software of the main control system will mainly implement the following functions:

- ➢ Selection of detection azimuth and depth
- ➢ Formulation of CAN Bus communication agreement
- ➢ Implementation of Digital phase sensitive detection (DPSD) algorithm
- ➢ Emission of radio frequency pulse sequence
- ➢ Generation of control timing for each module
- ➢ Acquisition and storage of echo signals