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Full-Signature Real-Time Corrosion Detection of Underground Casing Pipes

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Abstract—Corrosion monitoring and early detection of pits and wall thinning for casing pipes are considerably important to gas and petroleum industries since the frequently occurring corrosion at the internal or external parts of those steel casing pipes used in underground gas storage or oil fields causes production and environmental protection problems. In this paper, a new version of the direct current (dc) electromagnetic induction system is introduced in which a sensor system, based on the dc electromagnetic induction instrument, is coupled with an updated data acquisition system. Unlike the conventional dc induction instrument, the new system can achieve a *full-signature* logging response by providing all the measured flux leakage (FL) signals and eddy current (EC) signals to the computer logging system (CLS) on the surface.

To transmit the information represented by large amounts of data acquired by downhole instruments to the CLS on the surface, a wavelet data compression technique has been incorporated. A VLSI integrated circuit (IC) which realizes the wavelet transform has been designed so that the real-time mode can be achieved during the logging operation. The circuit has been designed using CMOS n-well 2- μm technology and has been fabricated by MOSIS.

Index Terms—Corrosion, eddy currents, electromagnetic field, Fourier transforms, microprocessors, wavelet transforms.

I. INTRODUCTION

CORROSION frequently occurs on steel casing pipes used in underground gas storage or in oil fields. Pitting or wall thinning often occurs internally as well as externally. More seriously, corrosion will form holes through casing pipes, which causes operational problems and environmental protection hazards. Therefore, many oil and gas wells are required to be constructed from two or more concentric string pipes, which raises the cost of well completion and hence makes the corrosion monitoring and early detection of pits and wall thinning on casing pipes more significant.

The traditional instrument of detection was mechanical, probing inside the pipes in search of corrosion. It is very difficult to maintain, and is not capable of detecting any corrosion outside the casing pipes. Electromagnetic instruments are more convenient for pipe inspection because of their high sensitivity to various types of defects, their small size and light weight. Hall-effect instrumentation can usually be adopted for the measurement of flux leakage (FL) and eddy current (EC)

signals, but it cannot survive high temperatures and will provide inaccurate output if the environment is higher than 100 °C. The downhole pipes we inspect are 20 000 ft underground, where the temperature is as high as 175 °C. Any instrumentation which has a high power consumption and problems with heat dissipation cannot function properly and reliably there. Pick-up coil instrumentation is the only promising use for the electromagnetic approach. Still, a number of issues need to be addressed before it can be applied in the oil fields.

In the application of logging operation systems, not only an intensive logging sample rate is required (over 32 samples/ft, compared with the original 2–4 samples/ft) but also a high logging speed (over 100 ft/min compared with the original 20–30 ft/min). Here, large amounts of data are acquired while the data transmission speed (via the logging cable) is limited. In the past, some data obtained by the instrument were discarded during the logging. This made the interpretation of the logging record very difficult, since that discarded data may have contained very important information about the casing pipes being logged. In our new system design, a wavelet data compression technique is incorporated into transmitting the information represented to the surface through the enormous data acquired by downhole instruments. Unlike the old system in which only some of the FL and EC signals were transmitted, the new system can compress the data with wavelet technique, transmit them within the limited channel capacity, and then reconstruct the data to obtain a *full-signature* logging response. The comprehensive measurement allows a comprehensive interpretation and accurate differentiation of corrosion on the casing pipes.

Currently, the field customers require that well logging instruments be operated in real-time mode, and expect the data (logging plot) to be displayed at the well site during the logging process. The applied wavelet transform, however, is computationally intensive, which appears as a significant challenge to real-time operations. To accommodate this massive computation, parallel approaches must be adopted for which hardware implementation can be considered. We included on the VLSI chip, a fast wavelet transform algorithm so that the real-time mode can be achieved.

The circuit has been implemented using CMOS n-well 2- μm technology. The simulation and test results show that the design is advantageous and the circuit performance is satisfying.

Wavelet compression has never been applied to instrumentation and measurement in well logging industries. Presented is a unique piece of work incorporating wavelet data compression with a VLSI chip. The application specified integrated circuits (ASIC) design we innovatively accomplished has made real-time logging feasible. The full-signature response achieved

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is significant to cased-hole inspection. Prior to this effort, no research work was reported in the literature investigating ASIC, incorporating the wavelet technique as applied to well logging industries.

II. THE DC INDUCTION INSTRUMENT

A magnetic coil in the dc electromagnetic induction system generates a stable magnetic field from direct current, within and surrounding the casing wall. The corrosion pits inside or outside the casing walls will cause field irregularity (or FL) which will be detected by certain sensors. The electromagnet and the sensor assembly are housed in a sonde section. The controller electronics module is mounted on the top of the sonde section by a mechanical joint, and controlled by the computer logging system (CLS) on the surface. The sensor coils are housed in pads (or shoes) which are held against the casing wall as the instrument traverses the casing. The instrument traverses at a constant logging speed so that the accuracy of measurement can be maintained [1]. There are, in total, 48 sensor coils within two rows of pads. The sensor pads are designed to overlap one another around the circumference of the sonde section. In this way, a complete survey can be conducted.

A. The FL and EC Signals

An electromagnetic field is produced by injecting a dc current (generated at the surface) into the coil of the electromagnet housed in the mandrel. This static magnetic field in the core is coupled to the casing pipe across an air gap at the poles of the electromagnet. The field is uniform in a section of casing pipe without defects. However, in the presence of defects the field is disturbed, and flux lines leak out of the casing pipe wall. The signals of FL can be detected when the sensor coils are passing the defective area.

According to Maxwell's equations and Faraday's Law, the *electromotive force (EMF)*, which is also referred to as the induced voltage across the FL sensor coils to the FL, can be expressed as

$$\begin{aligned} \text{EMF} &= - \int \int \frac{\partial \mathbf{B}}{\partial t} \cdot d\mathbf{S} + \oint d\mathbf{l} \cdot (\mathbf{v} \times \mathbf{B}) \\ &= - \int \int \frac{\partial \mathbf{B}}{\partial t} \cdot d\mathbf{S} - \oint \mathbf{B} \cdot (\mathbf{v} \times d\mathbf{l}). \end{aligned} \quad (1)$$

By the magnetic analysis program which uses a finite element approach, we can obtain the numerical solutions of the above equation. Empirically, an equation of the form

$$\text{Penetration depth(\%)} = C1 \ln(|(\nabla \times \mathbf{E})|C2 + 1) \quad (2)$$

can be used to generate interpretation charts. Constants $C1$ and $C2$ are determined by the data obtained from actual casing pipe samples in order to guarantee the accuracy of measurement.

Also, the changes in amplitude of EC's can indicate the possible locations of corroded regions (see Fig. 1). Here, injected into the coil is a high-frequency alternating current by which an alternating magnetic flux field is generated. With the coil placed parallel to the conducting material (casing pipes), the

Fig. 1. FL and EC signals.

eddy (or Foucant) current is induced, in a direction which resists the change in the injected flux field. The circulating currents generate their own magnetic fields, where the polarity is opposite to the original field. Acting as a load of the coil, the opposing fields will affect the amplitude of the current passes through the coil. An indication of changes in the internal wall of casing pipes can be obtained by measuring the change in the current injected into the coil. The amplitude of the injected current increases when an EC coil passes an internal defect, as if the casing wall moves away from the coil. The amplitude returns to normal when the coil passes the defect, as if the wall moves toward the coil. A skin effect can be generated by keeping the frequency of the injected current high, so that the EC set up in the casing pipes will be presented to the inner surface only. The EC signal is mainly used to discriminate between the internal and external corrosion pits since it will not respond to any external corrosion pit.

B. The Circuit

A block diagram of the dc induction instrument electronic circuit is shown in Fig. 2. The diagram contains three blocks: a controller electronics module and two analog cartridges (upper/lower). The core of the controller electronics module includes two microprocessors as well as control circuits. The two cartridges have identical circuits, each processing one array of pads with both FL and EC coils. Twelve individual FL and EC circuits are contained within an analog cartridge. A low-noise pre-amplifier is adopted to amplify the received FL signal and to suppress the "road noise" which is generated when the sonde section traverses through casing pipes during logging. Signal-conditioning circuits and analog-to-digital converter (ADC) circuits are also housed in the two cartridges. Each FL signal is conditioned and filtered into a separate channel. Moreover, the EC signal is modulated by a high frequency. A "skin effect" on the internal wall of the casing pipe is generated due to the high-frequency current through the EC coil so that the modulated EC signal will only respond to the internal corrosion on the wall of the casing pipe. Each received EC signal is conditioned and amplified in a separate channel. Then, all the amplified FL and EC signals are fed into the multiplexer circuits and the ADC. The ADC and the multiplexer circuits are controlled by the microprocessor, and each FL or EC signal can be accessed individually. The data or (digitized signals) are stored in RAM and transmitted to the CLS on the surface for recording.

Fig. 2. Block diagram of the electronic circuit of the dc induction instrument.

The CLS on the surface issues the data acquisition and transmission commands continuously, when the logging survey is being performed. As a response, the instrument performs the acquisition of data sets (including FL and EC) and transmits them to the CLS on the surface. For every foot of casing pipe being surveyed, these commands are repeated 32 times. That is, for every foot of casing pipe, 32 data sets (including FL and EC) are sampled, transmitted to the CLS on the surface, and recorded. Here, the sample rate is relatively high, and only through such a high sample rate (32 samples/ft) can the acceptable resolution of the logging survey be guaranteed. As indicated before, it is the goal of the dc induction system to detect small corrosion pits on the wall of casing pipes. The logging speed of the dc induction instrument must be high enough, on the other side, to obtain a certain level of signals from the FL or EC sensor coils, hence assuring a satisfying signal-to-noise ratio (SNR). A constant logging speed must be maintained in order to keep the accuracy of the measurement. At present it is set to 100 ft per minute. The logging survey by the dc induction instrument can only be performed at the time that the instrument is being pulled up in the casing pipes.

Given the high logging speed of the dc induction instrument and the amount of data acquired, two microprocessors are incorporated in the controller in order to reduce the overhead. One is dedicated to the data acquisition and the other is dedicated to communication, including the telemetry operation and data transmission. With the data transmission rate limited by the characteristics of long wirelines, however, it is impossible to have all of the EC signals transmitted. Only the 24 FL signals and the two largest EC signals could be transmitted in the past, while other EC signals were discarded. A new approach must be introduced if we are to obtain the complete information about underground pipes, without affecting any major change

in telemetry systems and maintaining the current rate in FL and EC signals transmission.

III. DATA TRANSMISSION TECHNIQUE

A. Wavelet Transform

In our system, the wavelet transform is adopted in order to transmit compressed data (FL and EC signals) to the CLS on the surface. As shown in [2], [3], the wavelet transform is more effective in analyzing the nonstationary signals than the Fourier transforms. It allows us to “zoom in” to specific areas of the signal with various scales, and hence can be used for multiresolution signal (MRS) analysis.

Unlike the short-time Fourier transform (STFT) [4], the wavelet transform uses short windows for high frequencies, and long windows for low frequencies. With the change of window sizes being referred to as the scale, the wavelet transform is the so-called time-scale representation of the time series [5]. However, the uncertainty principle [6] reveals that the resolution in time and frequency cannot be arbitrarily small, because their product is lower bounded by

$$\Delta t \Delta f \geq \frac{1}{4\pi}. \quad (3)$$

Here, one can only trade frequency resolution for time resolution, or vice versa. Since it meets the bound with equality, Gaussian windows are often used.

1) *Continuous Wavelet Transform (CWT) and Discrete Wavelet Transform (DWT)*: Suppose $x(t)$ is a continuous time signal. Then the normalized continuous wavelet transform of the signal with respect to $\Psi(t)$ is defined as [7]

$$\text{CWT}_{\Psi}(a, \tau) = \frac{1}{\sqrt{|a|}} \int_{-\infty}^{\infty} x(t) \Psi^* \left(\frac{t - \tau}{a} \right) dt \quad (4)$$

Fig. 3. Wavelet coefficients.

where function Ψ is the basic wavelet. Variable a determines the dilation or compression of the basic wavelet while τ is the time displacement.

The original time signal $x(t)$ can be reconstructed from $\Psi(t)$ by

$$x(t) = C \int_{a>0} \int \text{CWT}_{\Psi}(a, \tau) \Psi\left(\frac{t-\tau}{a}\right) \frac{da d\tau}{a^2} \quad (5)$$

where C is a constant that depends only on $\Psi(t)$. Several wavelets have been found suitable for the signal reconstruction in the CWT.

For the discrete wavelet transform, let T be the sampling time. Then we have $a = a_0^j$ and $b = k a_0^j T$ where j and k are integers. The corresponding discrete time wavelets are

$$\Psi_{j,k}(t) = a^{-j/2} \Psi\left(\frac{t}{a^j} - kT\right). \quad (6)$$

To obtain the wavelet coefficients, we have [8]

$$c_{j,k} = \int x(t) \Psi_{j,k}^*(t) dt. \quad (7)$$

Given the wavelets and their coefficients, the original time series can be reconstructed by

$$x(t) \approx C \sum_j \sum_k c_{j,k} \Psi_{j,k}(t) \quad (8)$$

with C being a constant independent of the signal.

2) *Multiresolution Analysis (MRA)*: A major application of the wavelet transform is in multiresolution analysis (MRA). A time series $x(n)$ can be scaled down to a given level. At each level, the scaled time series contains the low-frequency portion

of the signal. The difference between the original time series and the scaled time series is then called the wavelet series [9]. The above scaling procedure can be carried on repeatedly.

Suppose P_0 is the discrete approximation of the original time series $x(n)$, and P_1 is the first-level scaled time series where the scaling factor is 2. Then Q_1 , the first-level wavelet series, is the difference of the original time series and the scaled time series

$$Q_1 = P_0 - P_1. \quad (9)$$

At the n th scale level, P_n is the scaled version of P_{n-1} , and we have the n th-level wavelet series

$$Q_n = P_{n-1} - P_n. \quad (10)$$

The original approximation of the time series can be written as

$$\begin{aligned} P_0 &= P_1 + Q_1 \\ &= P_2 + Q_2 + Q_1 \\ &= P_3 + Q_3 + Q_2 + Q_1 \\ &= \dots \\ &= P_n + Q_n + Q_{n-1} + \dots + Q_1 \end{aligned} \quad (11)$$

where Q_j is the residual information at the j th level of scaling, and P_n is the information left after 2^n times of scale-down.

Given P_n and Q_j , with $j = 1, 2, \dots, n$, different signal processing techniques, such as differential pulse coded modulation (DPCM) or vector quantization, can be applied at different levels, thus achieving the best results.

3) *Application of Wavelet Transform to Lossy Data Compression*: The discrete wavelet transforms are essentially sub-band

Fig. 4. Comparison of the original signal to the reconstructed signal.

Fig. 5. Comparison of the original FL signal to the reconstructed FL signal after the compression in circumferential direction.

coding systems. In addition to its success in speech and image compression [10], the wavelet transform can be immediately applied to data compression [11].

Given the enormous amount of data resulting from the high logging speed and the intense logging sample rate, the bandwidth of the regular wirelines is too limited. Some important data are discarded and, as a consequence, the unintentionally excluded data cause an incomplete or incorrect logging

Fig. 6. Comparison of the errors for three sets of data to regular logging.

interpretation. In order to transmit the most significant information to the CLS on the surface, the wavelet technique is utilized.

The Daubechies wavelet of 4-tap, D_4 , was adopted which is regular and orthogonal to its even translates. It is natural and economic, matching with our 48 FL and EC signals. There are other wavelets which are also of 4-tap, such as the Haar wavelet. However, an obvious disadvantage of the Haar wavelet is that

Fig. 7. Block diagram of wavelet chip.

it is not continuous and therefore not a good choice for representing smooth functions.

The data in our system are acquired by the microprocessor controlled circuit. Each FL or EC signal previously mentioned is individually digitized. Although the logging speed is high and the logging sample rate is intense, only a subset of the acquired data could be transmitted in the past, such as FL1, FL2, ..., FL24, as well as the two largest pieces of EC data. This is because the bandwidth of regular wirelines is very limited, and as a result, the transmission rate of the logging cable is reduced. Here, significant amounts of EC data were unintentionally discarded. As a consequence, incomplete or incorrect logging interpretation was caused. To provide the CLS on the surface with the complete information about the corrosion of underground casing pipes, the wavelet technique should be utilized.

The amplitude of FL signals, which reflects the depth of corrosion pits on the walls of casing pipes, is used to interpret the extent of corrosion. The EC signals, which only occur when the corrosion pits are located on the internal wall of casing pipes, are

used to distinguish whether a corrosion pit is inside or outside the casing wall. As the wavelet transform is applied to both FL and EC signals, the digitized FL and EC signals (or data) in the dc induction instrument are converted into wavelet coefficients, including two components: the “spline” (or blur) and the “detail”. The spline contains the information about the amplitude of FL and EC signals, while the “detail” portion contains the details of FL and EC signals relevant to the shape of the signals. In terms of the FL signal, the amplitude of FL is what we care about, instead of the shape of the signal. Hence, the spline portion is the most significant part of the FL signal, interpreting the extent of the corrosion in the logging results. In terms of the EC signal, its presence or absence is significant, since it indicates whether the occurrence of corrosion on a casing pipe is internal or external. Retaining the largest two EC signals and dispensing with the rest, as has been done in the past, is certainly undesirable because it causes a misinterpretation of the location of corrosion. On the other side, conservation of all the details of the EC signals is unnecessary. Actually, it is sufficient to have the spline portion of EC signals transmitted but leave out the

“detail” portion, as long as the EC signal at every sample point is considered. In general, the “detail” portion of both FL and EC signals can be ignored in some aspects without losing significant information.

Small wavelet coefficients reflecting the details of FL and EC signals are ignored so that the data compression can be gained. Fig. 3 shows a set of wavelet coefficients converted from FL and EC data. It can be seen that the “spline portions” of wavelet coefficients, which are much bigger numbers, represent the significant portion (or low frequency) of FL and EC signals. These wavelet coefficients will be transmitted to the surface to reconstruct the FL and EC data. The “detail portions” of the wavelet coefficients, which are represented by smaller numbers, represent the finer portion (or high frequency) to be discarded so that data compression can be achieved.

A threshold is set to manipulate the coefficients in order to achieve the best tradeoff between the compression ratio and the root mean square error (RMSE). Instead of transmitting the FL and EC data directly to the CLS on the surface, the wavelet coefficients, of which the number of bytes are reduced substantially, are transmitted to the CLS on the surface. These coefficients are then reconstructed back to the original FL and EC signals. Fig. 4 shows the original data and the reconstructed data. It can be seen that there is almost no difference between the reconstructed signal and the original signal.

During the operation of casing inspection, each pad collects continuous FL and EC signals while the depth of the logging instrument in the well changes. However, the data must be compressed along the circumferential direction of casing pipes due to the following reason: in order to reflect the detailed corrosion situation of underground pipes, 48 pieces of FL signals and EC signals are collected along the circumferential direction of the casing pipe, each two by a pad staggered around the sonde. To achieve the real-time mode, all 48 FL and EC data must be transmitted immediately after they are acquired. In addition, due to the high logging speed and high sampling logging rate, the 48 sets of data must be compressed first before they are transmitted.

Fig. 5 shows the comparison of the reconstructed data with the original data after it is compressed along the circumferential direction. It can be seen that the reconstructed data is almost identical to the original data. The loss can be ignored, and the interpretation will not be affected.

4) *Error Analysis of the Lossy Data Compression:* It is a lossy compression we conducted to compress data. The following analysis has been conducted to understand the errors which might be caused through such compressions. A few sets of real data obtained from the field were tested. Set 1, set 2, and set 3 data, referred to in Fig. 6, are from 55 ft of logging of different regular casing pipes. Different thresholds were selected for different compression ratios, with respect to a data set. The data compressed under each threshold were then reconstructed. The errors between the reconstructed data and the original data were analyzed, and the RMSE for each set of data was calculated correspondingly. For set 1, set 2, and set 3 data, the RMSEs versus the compression ratios are plotted respectively.

In our system design, the compression ratio we selected is 2.4. This ratio is sufficient in the sense that the compressed data fit into our transmission channel capacity. The RMSE's obtained

Fig. 8. Layout of wavelet VLSI chip.

under this ratio are 0.3223, 0.3320, and 0.3659 for set 1, set 2, and set 3, respectively. We thereby believe that a good tradeoff between the distortion of data and the compression ratio has been achieved.

B. VLSI Chip Integrating Wavelet Technique

A VLSI chip has been designed which can perform, in a parallel fashion, the calculation of wavelet coefficients. As a matter of fact, the wavelet chip converts the FL and EC data to the corresponding wavelet coefficients. These coefficients are manipulated according to the threshold, transmitted to the CLS on the surface, and then reconstructed to the original FL and EC signals.

We designed the wavelet chip with a standard cell approach and implemented it with CMOS 2- μ m technology. As shown in Fig. 7, the chip is composed of two parts: 1) input/output data latches and control circuits and 2) an arithmetic logic unit (ALU).

Fig. 8 shows the photomicrograph of the chip we designed with the VLSI technology. CAD tools (OCTTOOLS and MAGIC) were employed to help the chip design and layout. The results from the OCTTOOLS simulation are plotted in Figs. 9 and 10. From Fig. 9, it can be seen that the difference between the original and reconstructed signals is very small and can be ignored. In Fig. 10, the difference between the original and reconstructed EC signals is noticeable; however,

Fig. 9. Simulation results by OCTTOOLS: FL signals.

Fig. 10. Simulation results by OCTTOOLS: EC signals.

TABLE I
WORST CASE DELAY TIME OF DEVICES

Device	Delay in worst case
Input DEMUX (AND)	25.48 ns
Input Register (D-FF)	8.49 ns
ALU	188.97 ns
Output Register (D-FF)	8.49 ns
Output Gate Array	4.45 ns

as described previously, the EC signals are used to discriminate between the internal and external corrosion only, so that such a type of difference will not affect the logging interpretation. Listed in Table I are the worst case delay times for different

devices such as DEMUX, Register, and ALU. The upper bound delay for the wavelet chip can be obtained by adding them together.

The transistor count on the chip is 9356 in total. The chip area for the latches is $1240 \times 1515 \mu\text{m}^2$, and that for the ALU is $2416 \times 3875 \mu\text{m}^2$. The total chip area for the combination of latches and ALU is approximately $2600 \times 6000 \mu\text{m}^2$. The chip layout is framed using a standard pad frame of $4600 \times 6800 \mu\text{m}^2$ with 40 pins.

IV. CONCLUSION

A new version of the dc electromagnetic induction system has been presented which is capable of detecting small, isolated corrosion pits and holes on the casing wall, as well as transmitting the information represented by the large amount of data acquired by the downhole instrument to the CLS on the surface. A sensor system based on the dc electromagnetic induction instrument is coupled to an updated data acquisition system. Because of the high logging speed and high sampling logging rate, the acquired data must be compressed before being transmitted to the surface. A wavelet data compression technique has been incorporated which allows us to “zoom in” on a specific area of the signal with various scales based on the MRA. In this way, *all* the measured FL signals and EC signals can be transmitted to the CLS on the surface, without major changes to the existing telemetry system and the current transmission rate.

Unlike the conventional dc induction instrument, this system records *full-signature* logging responses and accurately differentiates the casing pipe hardware from the corrosion. The complete FL and EC signals increase the information available to log analysts, and facilitate the interpretation of corrosion on casing pipes.

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