Ultrasonic Nondestructive Testing in Oil wells

ULT-03

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ABSTRACT: Various ultrasonic techniques have been developed to answer specific questions during the life of an oil well. When the rock surface is directly accessible, an ultrasonic reflection image provides a means to identify geometric features like rock fractures. After the hole has been cased with a steel pipe and cement injected in the annulus, a transducer evaluates the acoustic impedance of the annulus material and checks the effectiveness of the cementing operation. Another transducer can provide a high resolution monitoring of the pipe corrosion. High pressure, temperature and fluid attenuation all impose a harsh environment on the development of such techniques.

1-INTRODUCTION.

The construction of a typical oil or gas well starts with the drilling phase where the hole is filled with mud. The function of this mud is to lubricate the drill bit, to transport the rock cuttings to surface and to maintain the rock fluids in place by mean of a higher pressure inside the borehole. After drilling, the rock face is in direct contact with the mud, and it is advantageous to make various measurements of the formation properties at this stage. This is achieved by means of sondes carrying down various sensors and their associated electronics. These sondes are supported from surface by a cable, which also provides electric power and a telemetry link between sensors and surface. These sondes are usually moved along the borehole at constant velocity and the sensors response recorded versus depth. After drilling, the well is usually cased with a steel pipe and the annulus between steel pipe and formation is cemented. The crucial role of cement is to prevent hydraulic communication between different formation fluids. The lack of hydraulic isolation can potentially lead to loss of hydrocarbons from the reservoir into formations at other depths, pollution of water aquifer or hazardous gas leak at surface. The cement sheath also holds the pipe in place and protects its outer surface from corrosion by aggressive downhole fluids. After cement curing, it is required to assess the quality of the cement placement, again by means of a local measurement done by a sonde. Later in the life of a well, during production, the same cement measurement or new measurements such as formation evaluation through casing or identification of produced fluids may also be performed.

To address some of the measurements encountered at each phase, a general purpose ultrasonic tool has been developed (Figure 1). It is built around an interchangeable transducer operating in a pulse echo mode and rotated at 7.5 turns/second. The transducer is selected according to the measurement to be done, with three possibilities: A focused transducer is needed for reflection imaging of the borehole surface, either formation wall or the inside surface of the casing. An unfocused transducer is used to evaluate the material filling the annulus behind the casing, and a high frequency transducer allows high resolution corrosion evaluation of the casing. The sonde itself is mechanically centralized in the hole in order to insure normal incidence of the ultrasonic beam on the borehole wall.The electronic transmitter and preamplifier are located close to the transducer on a rotating shaft, and the connection to the rest of the electronic is made by a rotating transformer. This electronic controls the acquisition sequence, amplifies and digitizes the signals, and transmits the waveforms to surface for real time processing and display.

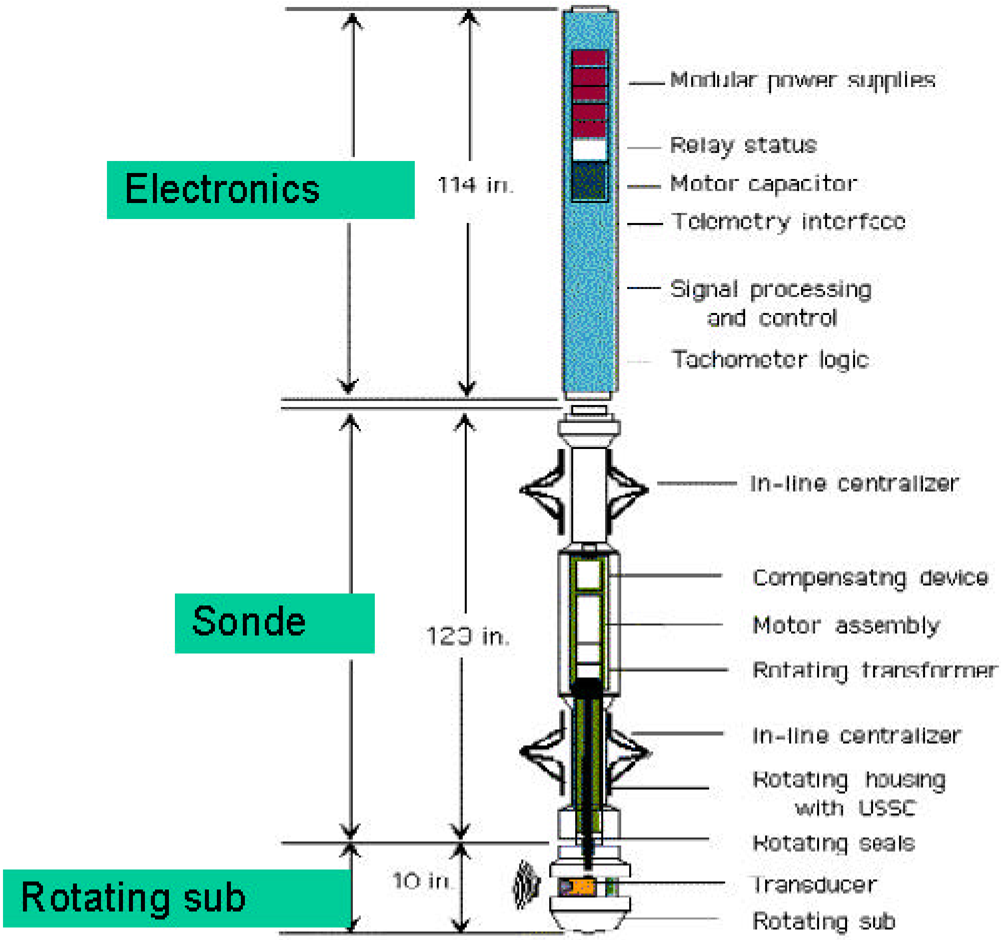

Figure 1: Schematic of the ultrasonic sonde.

2-BOREHOLE ENVIRONMENT.

The borehole environment puts severe restrictions on ultrasonic transducers and propagation. First the pressure and temperature encountered downhole are such that typical specifications are 1400 bar and 175° C. Such specifications limits the choice of materials available for transducers construction. Another constraint is the available room to fit a transducer since the maximum diameter of the sonde is less than 100 mm.

Then the borehole fluids may be varied (water, brine), but are often muds loaded with heavy mineral particles in order to reach a specified density. The mud density may reach a value of 2000 kg.m^{-3}, which not only creates a wide range of fluid acoustic impedances, but also leads to a high ultrasonic attenuation. This attenuation, approximately proportional to frequency, is up to 12 dB/MHz/cm and severely limits the maximum usable frequency and distance range. To mitigate the range problem, the transducer distance to the wall is adjusted before tool operation.

Acoustic properties of materials of interest are listed in Table 1. Rock acoustic properties are also affected by porosity, while cement properties depends on composition which can be adjusted to lower the density for specific purposes.

Material	Density (kg.m^{-3})	Acoustic velocity (ms^{-1})	Acoustic Impedance
Water	1000	1500	1.5
Drilling fluids	1000-2000	1300-1800	1.5-3.0
Limestone	2700	6400	17
Sandstone	2650	5500	14.5
Steel	7800	5900	46
Cement (regular)	1800-2000	3000-4000	5.4-8.0
Cement (light)	1100-1800	2700-3000	3.0-5.4

Table 1: Acoustic properties of borehole materials.

Finally, economic considerations impose a high speed of data acquisition since the depth intervals to be monitored are often of the order of several kilometers.

3-BOREHOLE IMAGING.

The first ultrasonic application is borehole imaging in order to identify geometric features of the formation [1]. Two measurements are made, travel time (converted into distance by using the measured fluid velocity) and reflected echo amplitude. To minimize mud attenuation, the wide-band transducer is driven by a single cycle of 250 or 500 kHz depending of the application. To get the optimum resolution and reduce sensitivity to borehole rugosity and tool eccentering, the transducer is focused with a diameter of 44 mm and a focal length of 63 mm. In low attenuation mud, the resulting 6 dB beam width is either 4.1 or 8.2mm depending on the frequency, with a significant depth of field. In high attenuation mud (12 dB/MHz/cm), the beam width is increased by about 50% due to the preferred attenuation of the high frequency components.

The spatial sampling is made consistent with the beam size and the borehole diameter (typically 216 mm), and is 5 or 10 mm in the vertical direction and 2 degrees in the horizontal plane. With the given transducer rotation speed of 7.5 Hz, these data specify the vertical displacement of the tool at either 137 or 274 m per hour. Because of the limited telemetry bandwidth, waveforms are digitally processed downhole, and only the amplitude and time of the reflected echo are sent to surface.

The results are displayed as images of amplitudes or radius. Tool eccentering effects on both amplitude and radius are corrected using an algorithm not affected by the presence of fractures and vertical breakouts. The amplitude image is affected by many factors such as angle of incidence, hole rugosity and radius, mud attenuation, impedance contrast between mud and formation. Fig.2 compares the ultrasonic amplitude image with 2 electrical resistivity images (high and low resolutions) in a crystalline fractured rock. It can be seen that the ultrasonic image is sensitive to the largest fractures through a rugosity effect at the intersection of the fractures with the borehole, but is less detailed than the highest resolution electrical image. However, the ultrasonic technique has the unique possibility of quantify borehole shape deformation such as breakouts, shearing of the borehole along a fault or erosion by drill collar.

4-CEMENT EVALUATION.

From an economic point of view, the most important ultrasonic technique is cement evaluation [2]. The challenge is to measure the acoustic impedance of the material present outside the steel pipe with a transducer located inside. The principle is to send a broadband ultrasonic pulse which excites the thickness resonance mode of the pipe. These thicknesses range from 4.5 to 15mm and to minimize mud attenuation, only the fundamental resonance (0.65 to 0.2 MHz) is considered. The reflected waveform (Fig.3) is made of a large initial reflection from the inside of the pipe, followed by the small amplitude exponential decay of the resonance. The decay rate is sensitive to the impedance of the material behind the pipe: The higher this impedance, the faster the decay, due to energy leaking into the annulus material. In the frequency domain, the resonance appears as a notch with increasing width and decreasing depth.

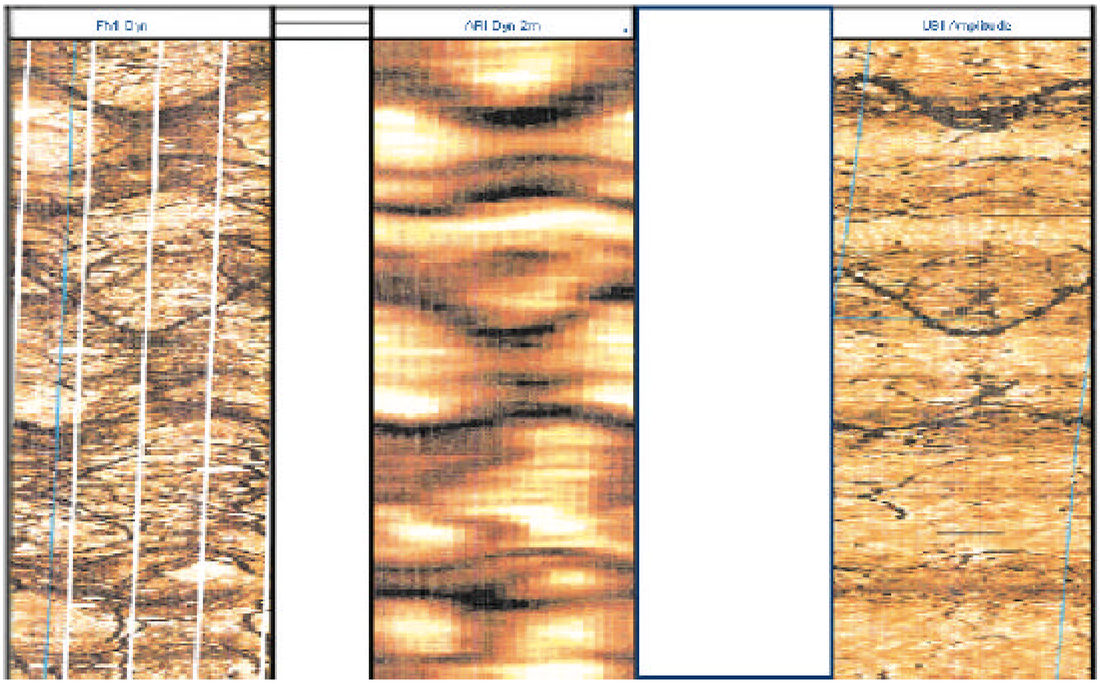

Figure 2: Example of ultrasonic amplitude image (right track) compared with high and low resolution resistivity images (left and center track). Vertical distance 13m.

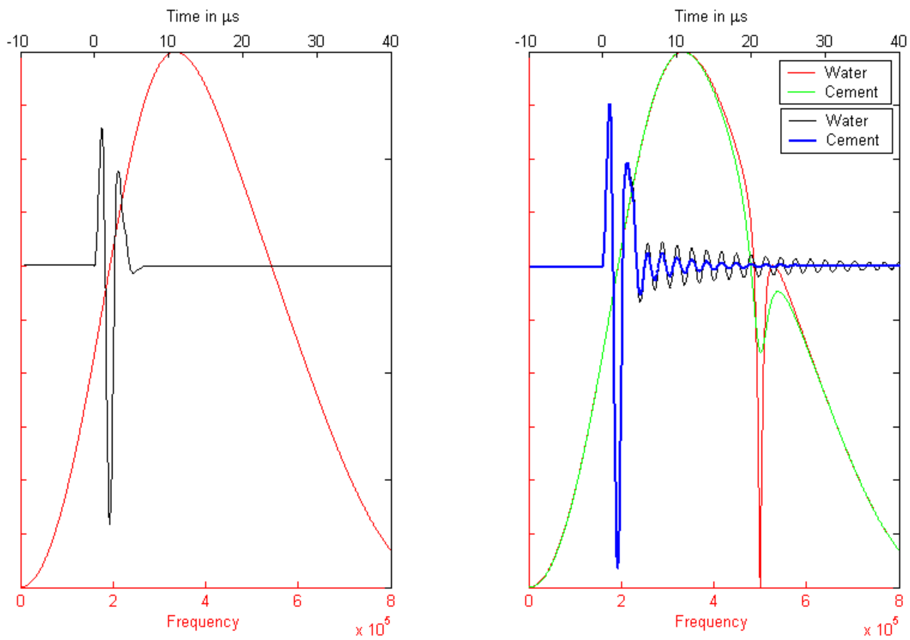

Figure 3: Modeled time and frequency response of the transducer after reflection on a single interface (left), and after reflection on a steel plate backed by water or cement (right).

The actual measurement is done in the frequency domain, on the group delay (derivative of the phase with respect to frequency) in order to be less sensitive to the transducer frequency response. The inversion is model-based with a fit of the resonance width by a simple planar model where the resonance frequency and the material impedance are the adjustable parameters. The results are then corrected for tabulated nonplanar geometry effects. Since mud impedance is also a factor in the decay rate, it has to be separately measured. This is achieved by rotating the transducer to a position where it is facing a fixed target plate with borehole mud present on both sides. The only unknowns are then the mud impedance and velocity. This fluid

characterization is done while the tool is tripping down the well while the cement evaluation is done on the way up.
The transducer itself is wideband to cover the pipe thickness range, with a compact impulse response free of interferences with the resonance decay. The beam width is unfocused to avoid the generation of unwanted modes in the pipe, with a diameter of about 25mm. The spatial sampling rate is typically 75mm in the vertical direction and 5 degrees in the horizontal directions, in which case the tool velocity reaches 500 m/hour. All waveforms are digitized and sent uphole for processing and storage. Beyond cement impedance, additional information is extracted from the waveforms. The peak echo amplitude gives an indication of the internal pipe condition, the echo travel time is converted into pipe internal diameter, while the resonance frequency is converted into pipe thickness since the steel velocity can be assumed to be constant.
An example of actual measurements is given in Fig.4. The left track is the amplitude image and display a dark line due to a wear groove, also appearing in the other images. The next track is a pictorial representation of a cross section of the pipe, where the measured pipe thickness is added to the measured pipe internal radius in order to get the external radius. The next two tracks show the images of the internal radius after correction for sonde eccentering and removal of the mean value. The right track is an image of the impedance of the material behind casing. The darker the brown shading, the higher the impedance. Below a given threshold, adjusted for the expected fluid impedance, the color is a uniform blue. This particular example display an undesirable discontinuous fluid channel covering approximately 50% of the circumference.

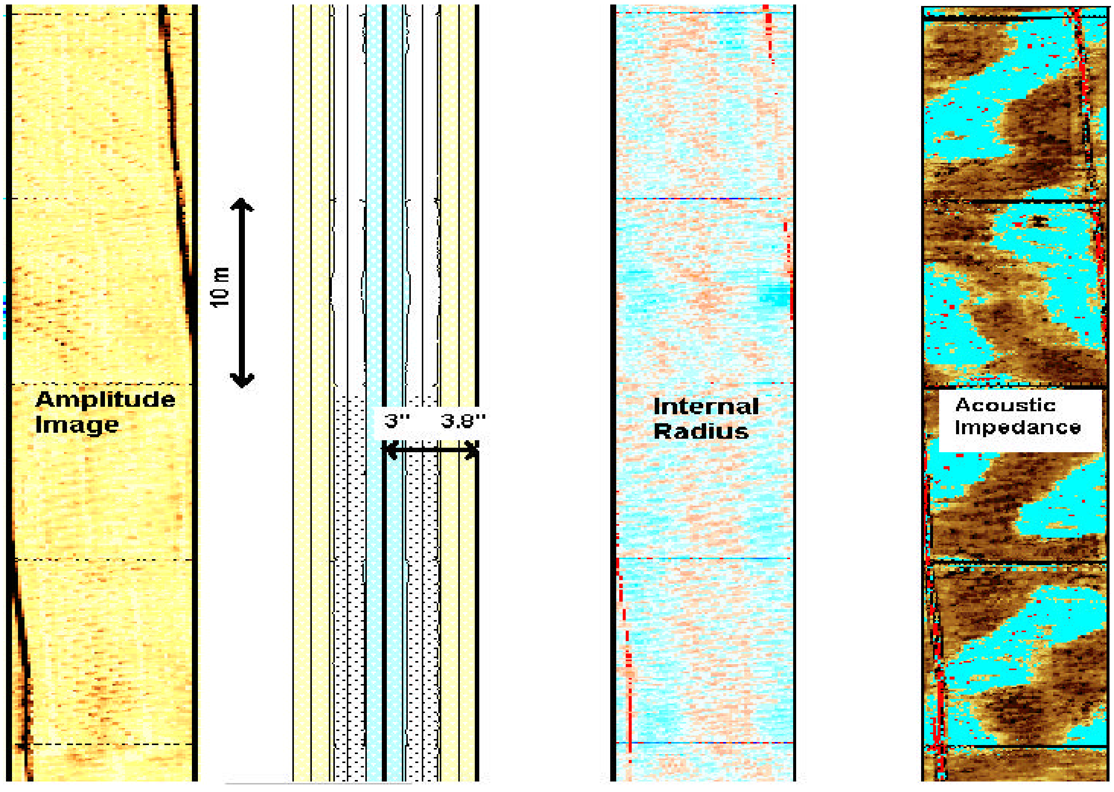

Figure 4 : Cement behind casing evaluation (see text for explanations).

5-CORROSION EVALUATION

Beyond cement evaluation, the previous technique also allows for corrosion evaluation, as long as the defects are not smaller than the beam width. To address the detection of smaller defects such as pitting, a third transducer has been developed. This is a 2MHz focused transducer, with a beam width of about 2.8mm and a focal length of 50mm. The spatial sampling and tool speed are identical to the first transducer (down to 5mm in the vertical direction and 2 degrees in the horizontal plane, speed down to 130 m/hour). Because of the high frequency, the internal and

external echoes can be separated, and the thickness computed from their time difference. The drawback is a limitation to operation in clear fluid due to attenuation.
Fig.5 displays a 3D representation of the measurements in short pipe sections (approximately 30cm), showing deep pitting and holes on the internal surface.

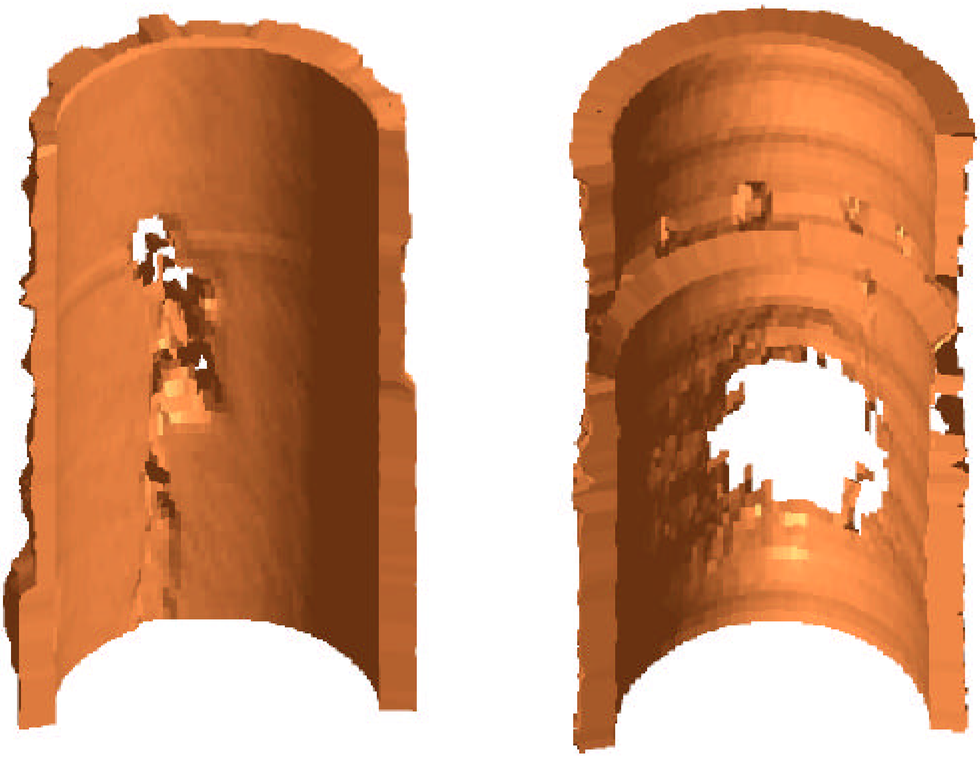

Figure 5: 3D images of short pipe sections from ultrasonic measurement of inner radius and thickness.

6-CONCLUSIONS

Various ultrasonic techniques have been developed for the difficult conditions of an oil well borehole. These techniques make possible rock surface imaging, evaluation of the effectiveness of pipe cementation, and extensive monitoring of corrosion or wear in steel pipes. They are routinely deployed over thousands of meters of wells in any location of the world.

REFERENCES

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