Well Integrity Evaluation with LWD – Quantitative Full Range Cement Bond Index

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ABSTRACT

This paper discusses well integrity evaluation using LWD sonic monopole data. The first part of the paper explains the methodology which enables full range cement bond index determination i.e. 0 to 1; a hybrid method which uses both amplitude and attenuation through a receiver array (Pistre et all, 2014). The methodology was enhanced at each processing step to be applicable in wide range of conditions including quality control of the processing results. The later part of the paper shows a real world example that demonstrates how the data was used as input to decisions regarding well integrity. With the example case study, the benefits of LWD cement evaluation were confirmed.

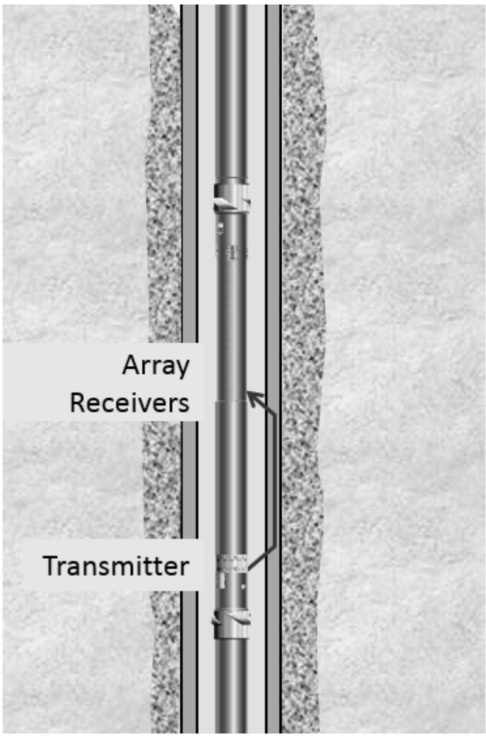

Figure 1: An LWD sonic tool is shown above inside casing. The signal which travels in the casing and arrives at the array receivers contains information which can be used to determine how well the cement is bonded to the casing.

Introduction of the methodology

The basic principle of sonic cement evaluation with Wireline is based on the acoustic signal of the casing extensional mode traveling through the casing. When no cement is present the casing is free to ring and the signal which reaches the receivers is large. Contrarily, when cement is present behind the casing, the casing extensional mode is attenuated and the received signal is much smaller.

In LWD sonic cement evaluation, drill collar acoustic propagation is one of the biggest concerns since it becomes mixed with the casing mode. The presence of the tool collar mode limits the bond index range which can be measured using an amplitude only approach (Blyth et. al, 2013).

In order to determine the cement bond index in high bonding conditions, an attenuation based approach is utilized. By looking at the change in amplitude across an array of receivers, the apparent attenuation of the casing mode can be determined. That rate of attenuation is then converted into a bond index value based on a model which takes both casing and collar modes into account.

By combining the bond index results of amplitude and attenuation based methods, a "hybrid" bond index is created allowing bond index determination up to 1. The amplitude result is used for lower bonding conditions; the attenuation result is used for higher bonding conditions. At the transition between the useful ranges of each method, a weighted average is used.

The following sections explain the detailed processing steps for the hybrid method and lists key operating considerations.

Signal Amplitude and Attenuation

Signal amplitude and attenuation are determined with the early part of the array waveforms in which casing and tool collar modes arrive at the receiver section. First, a waveform envelope is calculated for the receiver array of high-frequency monopole data. Then, amplitude and attenuation through the receiver array are calculated using a fixed time window (Figure 2). The amplitude on envelope and fixed time window are processing techniques enhanced for the hybrid method in order to obtain a robust attenuation trend.

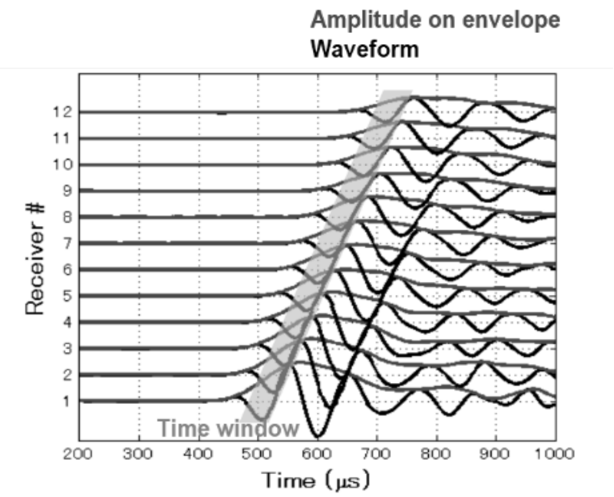

Figure 2: Early arrival detection for amplitude and attenuation through the receiver array

Bond Index Conversions

From the amplitude and attenuation described above, two bond index logs are calculated: amplitude-based and attenuation-based.

Amplitude-based bond index is calculated by converting the detected amplitude with a conventional linear model between the magnitude of the casing mode and cement bonding (figure 3, left). Using this method, the calculated bond index is reliable for lower bonding ranges in which the amplitude of the casing mode is much larger than that of the collar mode. Once the amplitude of the casing mode falls below that of the residual tool collar mode then the sensitivity of the measured amplitude to bond index is less and it basically measures the residual collar amplitude. Note that the amplitude-based bond index may work for higher bonding when the acoustic impedance of cement behind casing is low and/or the casing is thick (Kinoshita et. al, 2013) as in these scenarios the casing amplitude remains relatively high even at higher bonding.

The Attenuation-based bond index is calculated by converting the detected attenuation with a summation model in which both casing and tool collar modes are taken into account (Pistre et all, 2014). The model is computed using tool size, casing outer diameter and weight, cement acoustic impedance, and mud properties such as density and slowness.

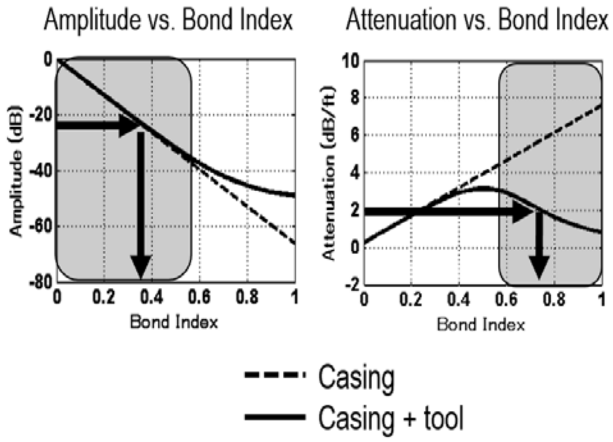

Figure 3: Bond index conversions for amplitude (left) and attenuation (right). Amplitude is used for lower bonding conditions while attenuation is used in higher bonding conditions,

The combination of casing and collar modes can be used to explain the bell shaped summation model (Figure 3, right). At zero bonding, the casing is free to ring and the amplitude of the casing mode is larger than that of the tool collar mode. As bonding increases so does the attenuation as long as the amplitude of the casing mode remains larger than the tool collar mode. Once the bonding becomes high enough that the casing mode is similar to or smaller than the tool collar mode, then the attenuation starts to show a decreasing trend. This is due to the increasing influence of the tool collar mode relative to the casing mode. The decreasing trend of apparent attenuation indicates that it is still sensitive to cement bonding. Thus, the attenuation-based method is an effective measure for cement evaluation in high bonding conditions compared to the amplitude-based method.

In very low bonding conditions e.g. bond index of 0.4 or lower in Figure 3, both amplitude and attenuation based methods have sensitivity to bonding changes. However, in the range 0.4 to 0.58 of Figure 3, the amplitude based method shows better sensitivity than the attenuation based method. It is for this reason that the amplitude based method is more robust over a wider range of lower bonding conditions.

The decreasing part of the bell shape trend in higher bonding range is used for the conversion of attenuation to bond index. Figure 4 and 5 show signal attenuation vs. bond index from a model-based study for 6.75-in. and 8.25-in. tools in different casing sizes and cement types.

The shape of each curve depends on logging conditions and indicates the bond index range in which amplitude-based and attenuation-based methods are applied. The shape also illustrates the sensitivity of the attenuation measurement to bond index. For example, in case of thin casing and high acoustic impedance cement (e.g. the bottom-right panel of the Figure 4) attenuation becomes flat in high bonding conditions, indicating that the sensitivity of attenuation to bond index is low. Thus, extracting a bond index is challenging in such conditions even with the attenuation-based method.

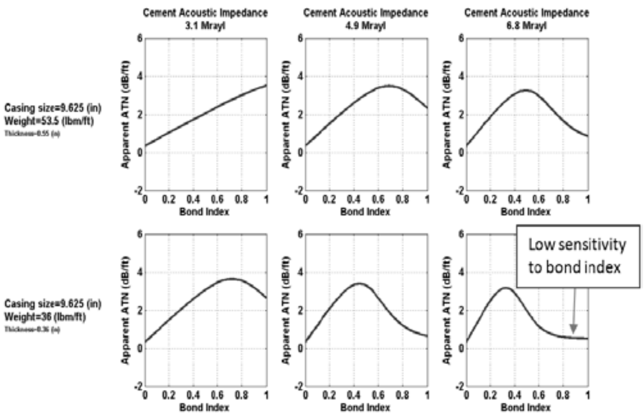

Figure 4: Modeled apparent attenuation vs. bond index for a 6.75-in. tool inside 9.625-in. casing.

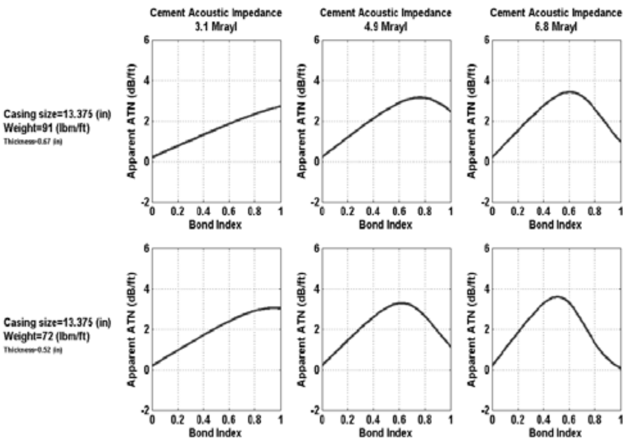

Figure 5: Modeled apparent attenuation vs. bond index for an 8.25-in. tool inside 13.375-in. casing.

Hybrid Bond Index

Two bond indexes based on amplitude and attenuation are combined into one hybrid log. In the transition range between amplitude and attenuation methods, a weighted average is used. The exact bonding range where the weighted average is used depends on logging conditions.

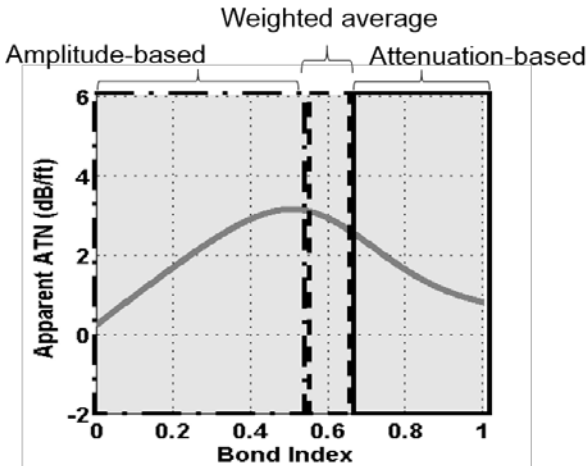

Figure 6: A modeled apparent attenuation vs. bond index curve is shown to illustrate where amplitude and attenuation based methods would be applicable and where the weighted average zone would be.

Operational Considerations

The hybrid method can be applied for common casing sizes logged as the LWD tools pass through to drill the subsequent open-hole section; i.e. 7” casing for 4.75-in tool, 9.625” casing for 6.75-in tool, and 11.75-in to 14-in casing for 8.25-in tool. In larger casing sizes, the annular space between the casing and tool becomes larger making the measured signal attenuation more sensitive to mud properties. Thus, only the amplitude-based method is applicable in very large casing (e.g. hybrid approach cannot be applied to 10.75-in. casing for 4.75-in. tool).

Even if the parameters are within the range of the hybrid method, the measurability of full-bonding could be limited due to the low sensitivity of the apparent attenuation to the bond index when the cement acoustic impedance is high in thin casing, as previously explained. The signal-to-noise ratio of the measured signal is another factor which may limit the measurability of full-bonding.

When the formation compressional slowness becomes close to or faster than that of the casing slowness, the ability to compute a bond index is also affected. Because the formation compressional and casing mode reach the receivers at nearly the same time it is difficult to distinguish one from the other. This limitation is common to LWD and Wireline alike, although the applicable formation slowness range may not be exactly the same due to different TR spacing. Figure 7 shows the applicability of LWD cement bond index relative to formation compressional slowness (DTc).

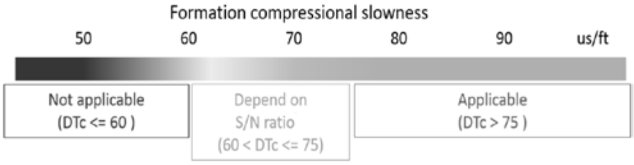

Figure 7: Applicability of quantitative cement evaluation with LWD sonic tools regarding formation compressional slowness

Tool centering and logging speed must also be controlled in order to obtain good results. Tool centering is achieved using screw on stabilizers sized for open-hole drilling and so care needs to be taken to ensure there is also adequate stabilization in the cased-hole section. Record rates as fast as 1-2 second can be used to obtain 2 samples per foot up to 1,800 ft. /hr.

Acquisition can be done while drilling out cement or during the final pull out of hole (POOH) pass. Performing the acquisition during the POOH will provide better SNR due to the lack of drill string rotation (e.g. less pumping noise, less noise from stabilizers rubbing the casing). Logging speed should be controlled to obtain 2 samples per foot. Data density is particularly important to obtain reliable data in high bonding intervals because the casing mode amplitude becomes smaller in such conditions.

In processing the data for the hybrid method, there is an option to stack waveforms in certain depth intervals to optimize SNR, but if the distance between samples is too far, the possible benefit of stacking is reduced. Logging too fast will also result in reduced vertical resolution.

Data Presentation

Figure 8 shows a hybrid bond index log. Track 1 shows open-hole gamma ray logged before casing was run. If any areas of low bonding are present, gamma ray can be referenced to help determine if this is related to the formation type or not. Track 2 shows monopole data obtained in cased hole. The compressional slowness value can be referenced to see if it is above the range expected to present processing difficulties (Figure 7). While the presence of a formation compressional may indicate the presence of cement, it is not necessarily an indication of high bonding.

Track 3 shows a well sketch which includes the casing inner and outer diameters as well as the casing shoe depth. Track 4 shows the depth reference and well bore inclination. If areas of low bonding are observed, well bore inclination can be referenced. For example, if well inclination goes above 90 degrees, it may correlate with low bonding, particularly at the bottom of a liner.

Track 5 shows three different bond index values (amplitude, attenuation, and hybrid). The transition area where a weighted average is used is denoted with straight lines. A confidence range for the attenuation based bond index is also shown. The confidence range corresponds to the stability of attenuation computed at multiple points across the fixed time window. If attenuation across the fixed time window is stable, the confidence range will be small. However if the computed attenuation values across the time window fluctuate, the confidence range will be wider. The confidence range is linked to the signal to noise ratio (SNR). Where drilling noise is high or where cement bonding is very good, a widening confidence range is expected.

Track 6 shows a flag indicating which bond index value is used for the hybrid curve: amplitude, attenuation, or a weighted average. Areas of low confidence can also be indicated. Track 7 shows the amplitude of noise and the casing amplitude at the receiver nearest to the transmitter. The amplitude of noise is computed in the time period before casing, collar, and formation modes reach the receivers. The amplitude at the nearest receiver is computed in the fixed time window detailed in Figure 1.

Lastly a VDL is shown in track 8 along with the fixed time window denoted by two straight lines. In areas where bonding is seen to be low, higher amplitudes can be seen inside of the fixed computation window. When bonding is high, very little or no signal amplitude can be seen visually in the fixed time window.

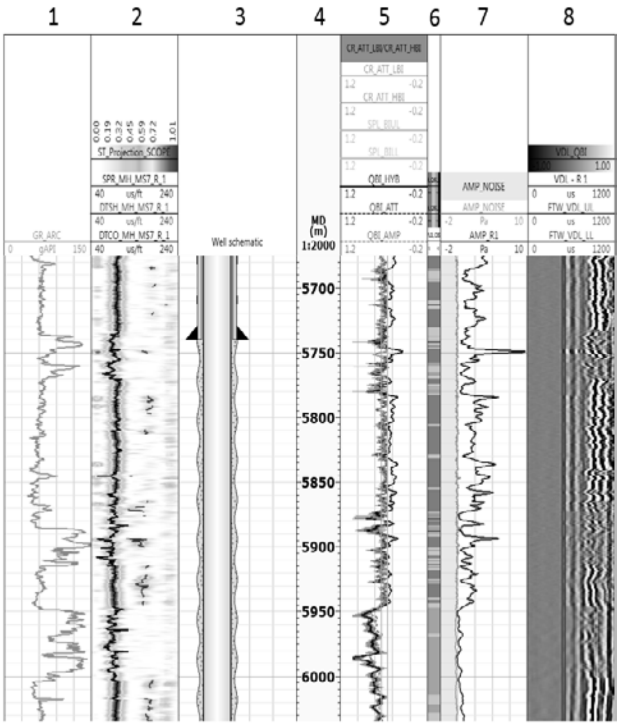

Figure 8: A log excerpt showing the hybrid bond index result and associated quality control indicators.

Case History

CNOOC planned to drill an ERD well from an existing platform to extract hydrocarbons in a faulted structure in the East China Sea. The well objective was to evaluate and produce from 4 gas reservoirs with the final completion plan pending on the result of logging data analysis. If the deeper reservoirs were still untapped by nearby wells, the plan was to produce from either one of the deepest reservoirs first then perforate the shallower two sands later for comingled production. If the analysis showed the deeper reservoirs to be depleted, then all reservoirs would be perforated at the same time.

To ensure safe production and no cross communication between the sands, good wellbore integrity and effective zonal isolation was very important. Due to the nature of an extended reach well, an LWD sonic tool was selected to provide cement bond analysis to reduce operational complexity and safety risks after setting the 7" production liner. Data was acquired while tripping upwards with a controlled logging speed below 274 m/hr. with the tool programmed at a 2 second record rate.

Analysis of the acoustic data showed good cement bonding at the bottom section over the target interval and low quality bonding above 5950m MD. This depth coincides with a lost circulation interval experienced while drilling. Over the interval below 5950m, bond index values of 0.5 to 1 are seen, mainly originating from the attenuation based computation. Above 5950m, bonding values taken mostly from the amplitude based computation range from 0 to 0.5.

An initial pressure test was conducted but did not reach the desired pressure. Using the information provided by this analysis, a remedial action was taken to perform a cement squeeze from the top between the 9 5/8" casing and 7" liner. A subsequent pressure test conducted up to 2600 psi positively confirmed the cement sheath integrity before perforation. Based on the open-hole logging data evaluation, CNOOC decided to produce from all 3 separate zones at once.

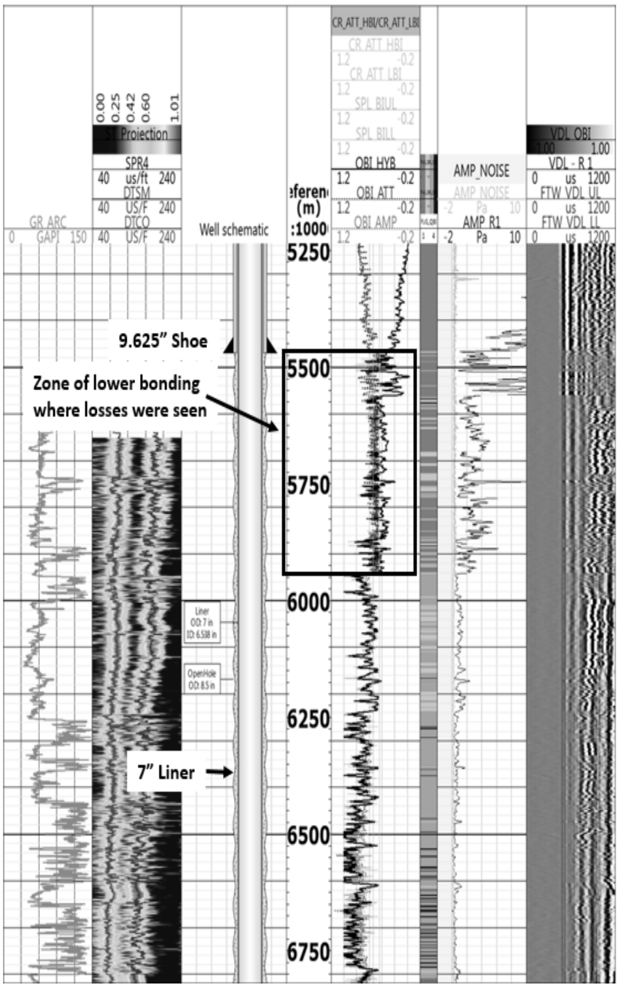

Figure 9: Zone of lost circulation correlated with low hybrid cement bond index values. A lack of good cement bonding was the reason the initial pressure test failed. The open-hole monopole data is shown for reference.

Conclusion

This paper has detailed a new method of cement bonding evaluation using high-frequency monopole data acquired with an LWD sonic tool. The method referred to as "hybrid" combines amplitude and attenuation based methods enabling a full range of cement bond index determination.

The fact that casing and collar modes arrive to the receiver array at nearly the same time has been accounted for in the processing methodology. The operational considerations discussed include applicable formation compressional slowness range, casing O.D., logging speed, tool centralization, and the insensitivity of attenuation to cement bonding in thin casing surrounded by cement with a high acoustic impedance.

A final data example was shown that demonstrates the usefulness of the measurement, in this case to confirm zonal isolation. LWD was chosen first of all for ease of conveyance in a high angle well. The resultant hybrid bond index log confirmed good bonding over most of the section.

The interval of low bonding just below the casing shoe correlated to lost circulation while drilling and a failing pressure test. After performing a cement squeeze the desired zonal isolation was positively confirmed with a second pressure test. This example clearly demonstrates the usefulness of the hybrid measurement to support decisions regarding well integrity

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