Experimental Study of an Advanced Three-Component Borehole Seismic Receiver

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SUMMARY

An advanced three-component borehole seismic receiver has been designed, developed, and tested. This receiver was designed with the aid of finite element vibration modeling to be free of significant clamp resonances below 2000 Hz. This broad frequency range makes this sonde well suited for cross-well seismic imaging applications. State-of-the art piezo-electric accelerometers are used as the three-component sensors and provide signal enhancement relative to conventional geophones. The use of these accelerometers offer a signal-to-noise enhancement of approximately 20 dB at 1000 Hz over moving-coil seismic geophones. Additional features of the sonde include high temperature/pressure operation, small size, lightweight, field-durable construction, and multi-station expansion capability. A prototype accelerometer-based sonde was field tested at the Texaco Humble Field to determine its performance characteristics. A borehole explosive source was used to test the sonde in a cross-well configuration (815 ft well-to-well separation). For comparison purposes, similar cross-well tests were performed using a commercial VSP-type tool and buried/cemented geophones. The advanced sonde exhibited significantly improved coupling relative to the VSP tool as evidenced by increased bandwidth and signal-to-noise ratio. Additionally, the advanced sonde produced signals which rival those produced by the buried/cemented geophones.

INTRODUCTION

The bandwidth associated with conventional surface-seismic and VSP techniques for imaging deep petroleum reservoirs (Coffeen, 1986) is typically less than 150 Hz. With the advent of cross-well seismic techniques, the bandwidth is potentially increased well beyond 150 Hz due to the shorter propagation paths and the improved seismic coupling at depth. As a result, there is now a need for both borehole seismic sources and receivers that have bandwidths on the order of 1000 Hz to take advantage of the high resolution capabilities of cross-well imaging (Bloch, 1990). It has long been recognized (Galperin, 1985), however, that conventional VSP wall-locked sondes exhibit structural resonances in the 150 Hz to 400 Hz range. The presence of such tool resonances results in significant distortion of the seismic signals recorded during high-resolution cross-well surveys. Therefore, it is desirable to develop a wall-locked three-component sonde that is free of resonances at least below 1000 Hz. Even with a resonant-free tool, however, new three-component sensors need to be investigated for this broad-band application. While conventional geophones are clearly the appropriate sensor for low-frequency applications (Stanley, 1986), their performance degrades at the cross-well seismic frequencies. Therefore, the optimal sensor for cross-well seismic sondes needs to be determined. A further limitation of conventional VSP-type tools is that they do not readily allow expansion to multi-station configurations. The ability to simultaneously clamp multiple sondes in a borehole is essential to the commercial success of three-component cross-well surveys.

Considering the limitations of existing borehole seismic sondes, a program was undertaken to develop a borehole seismic receiver with the following performance characteristics: no resonances below 1000 Hz and preferably no significant resonances below 2000 Hz; accommodates advanced seismic sensor technology that offers signal enhancement at the cross-well seismic frequencies; provides for multi-station inter-connection; and withstands the oil-well environment including elevated temperatures/pressures and rough handling. A prototype seismic sonde with these characteristics has been developed and tested. In this paper, we describe the features of this sonde and present cross-well seismic data obtained from the advanced sonde. The performance of the sonde will be illustrated by comparisons with field data from a commercial VSP-type tool and buried/cemented geophones.

SONDE DESCRIPTION AND DESIGN

The present configuration of the Advanced Borehole Receiver (patent pending) consists of two pressure housings terminated with standard Gearhart-Owens seven conductor cable connectors, one on either end of a clamping assembly section. One housing contains the triaxially arranged accelerometers and the other the electric gearmotor. This gearmotor drives a rectangular piston perpendicular to the tool using a right angle translation unit to clamp the tool into the borehole. Since the right angle translation unit resides outside of the pressure housings, a high temperature and pressure rotary seal is used to insure integrity where the drive shaft breaches the gearmotor bulkhead. A photograph of the prototype Advanced Borehole Receiver is shown in Figure 1.

The primary design criteria for the Advanced Borehole Receiver are given in Table 1. The philosophy used to obtain these criteria required breaking the design into problem areas that could be solved individually. The identified design problem areas were; 1) temperature and pressure, 2) minimal overall length and maximum outside diameter of 4 inches, and 3) frequency response of the tool. Initial design solutions which satisfied the environmental and size constraints were then studied using finite element analysis to determine the clamped-tool frequency response. The design process then involved various iterations until a final design prototype which met the specifications of Table 1 resulted.

The temperature and pressure criteria were met initially by using type 17-4 stainless steel with a quarter inch wall thickness for the pressure housings. High temperature and high pressure O-rings were used as seals at the critical surfaces. Also, a high temperature and pressure rotary seal was used at the bulkhead / drive-shaft interface. A standard right angle drive device was slightly modified to withstand the pressure and a directly replaceable version that will handle both the temperature and pressure is available. A high temperature electric motor with variable gear trains was selected as the drive mechanism. Since the motor resides inside a pressure housing, its pressure specifications are lower.

DISCLAIMER

The size and weight design constraints led to two possible clamp-arm mechanisms: an angular-type clamp-arm , as per conventional VSP tools; and the clamping piston concept. Angular-type clamp arms were then ruled out since initial finite element modeling indicated significant clamp-arm resonances below 1000 Hz. Various clamping piston arrangements were then investigated to meet the environmental, physical, and frequency response constraints. The resulting design is a rectangular clamping piston that is driven by an electric gear-motor perpendicular to the tool axis. The clamping piston allows for 1.5 inches of travel, and accommodates adapters to allow clamping in boreholes ranging from 4.25 in. o.d. to 9 in. o.d. For prototype testing, a standard Gearhart-Owens seven conductor cable head was adapted to the ends of the pressure housings.

In order to evaluate the frequency response of the design, finite element analysis using NASTRAN code was performed on a model of the design. This entailed creating a representative mesh of the entire tool and establishing anchor or pin points about which the tool could move or flex. Different test cases were run in which the number and location of the pin points were varied to determine if any tool resonances existed. The results of these tests indicated where modifications needed to be made to remain within the design goal. This process was repeated until the results indicated the potential for a flat tool response out to 2.0 kHz.

An important issue for this advanced seismic receiver was the selection of appropriate three-component sensors. Both theoretical and experimental investigations were undertaken to determine the optimal sensor for cross-well applications. As a result of these studies, we developed the required specifications for a signal-enhancing cross-well seismic accelerometer. These low-noise accelerometers were then custom manufactured by Wilcoxon Research, Gaithersburg, Md. It was found that the use of these low-noise piezo- electric accelerometers offer some significant advantages over conventional geophones. In particular, these accelerometers do not exhibit the 'spurious resonance' problem common to geophones (Stanley, 1986). Additionally, accelerometers are insensitive to their mounting orientation and therefore do not require the gimbal mounts often utilized in geophone-based sondes. Another difference, and perhaps most important, is that these custom-designed low- noise piezo-electric accelerometers are more sensitive than geophones at the cross-well seismic frequencies. This results since the electronic noise of the custom accelerometer is lower than the electronic noise of the best geophones at frequencies above approximately 150 Hz. To illustrate this point, Figure 2 displays seismic noise data measured with the accelerometers in two oil wells. The higher noise level in Well C30 results from nearby active oil-well pump-jacks. Also indicated in Figure 2 is the theoretical noise limit for moving-coil seismic geophones and the noise specification for the present low-noise accelerometers. It is apparent from Figure 2 that the accelerometers can offer as much as a 20 dB improvement in signal detection (and hence signal-to-noise ratio) at 1000 Hz.

A prototype sonde which meets the specifications of Table 1 was manufactured by OYO Geospace, Houston, TX. This prototype underwent significant laboratory testing to verify the clamping force, pressure integrity, frequency response, and compatibility with accelerometers. These laboratory tests served as a quality assurance measure prior to deploying the prototype in an oil-field environment.

Table 1

Advanced Borehole Seismic Receiver Specifications

Dimensions:	16" length by 4" o.d.
Weight:	30 lbs
Clamp force-to-weight ratio:	at least 5:1
Working Pressure:	10,000 psi
Working Temperature:	200°c (mechanical) 125°c (with current accelerometers)
Exposed Material:	Stainless Steel
Operates On:	7-conductor wireline (G.O.) or Multistation interconnect
First Computed Resonance:	2.1 kHz

CROSS-WELL SEISMIC DATA

During March of 1991, the advanced borehole seismic receiver prototype underwent a substantial set of field trials. The tests were held at the Texaco Humble Field Site near Houston, Tx. This site is an active oil-producing field with several wells available for cross- well seismic testing. At the site, both cross-well and VSP data were collected using the accelerometer-based sonde. Figure 3 is a representative data set obtained from the advanced sonde in the cross-well configuration. Figure 3 is a common-receiver gather (receiver depth of 1200 ft.) obtained in a cross-well configuration of 815 ft well-to-well spacing. The seismic source was a 10 gram explosive p-wave source (Chen et al., 1990) which generates wide-bandwidth signals. Figure 4 illustrates a common receiver gather for the same exact shots as used for Figure 3, but recorded by nearby cemented and buried geophones. The offset of the buried geophones from the source well was 1015 ft. In Figure 5, a commercial VSP-type tool was used to form a common receiver gather using the same parameters as Figure 3, i.e., 815 ft well-to-well spacing, with receiver clamped at 1200 ft depth.

Comparing Figures 3 and 4, it is clear that the basic character of the seismic sections is the same for both the buried geophones and the accelerometer-based sonde. In other words, the Advanced Borehole Receiver appears to couple adequately to the casing and is free from significant resonances in the pass-band (10 Hz to 1400 Hz). On the other hand, the commercial VSP tool, as indicated in Figure 5, produces "ringy" first arrivals indicative of resonances in the pass-band. Thus the advanced sonde provides for better coupling than the VSP tool at the cross-well seismic frequencies.

In order to quantify the signal-enhancement characteristics of the accelerometer-based sonde, spectral analysis of the p-wave arrivals from Figures 3, 4 and 5 was performed. Both average p-wave spectra and average noise spectra were computed for each section, thereby allowing a determination of the signal-to-noise ratio versus frequency. Figure 6 displays the results from this spectral analysis and clearly indicates the increased bandwidth and signal- to-noise enhancement of the accelerometer-based sonde. Specifically, note that the accelerometers offer an approximately 25 dB signal-to-noise enhancement at 1000 Hz relative to the buried geophones.

CONCLUSIONS

A prototype accelerometer-based seismic receiver has been designed, developed and tested. Cross-well seismic testing of the receiver indicates excellent coupling of the tool to the borehole to frequencies of at least 1400 Hz. The signals generated by the advanced sonde are considerably higher in resolution than those produced by a VSP-type tool. The receiver also appears to offer signal enhancement relative to buried and cemented geophones. This high resolution receiver should prove useful in improving the effectiveness of cross-well seismic surveys.

ACKNOWLEDGEMENTS

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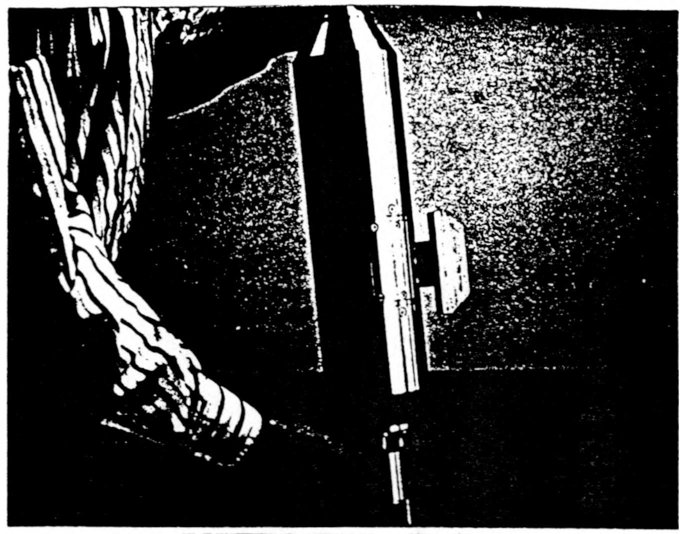
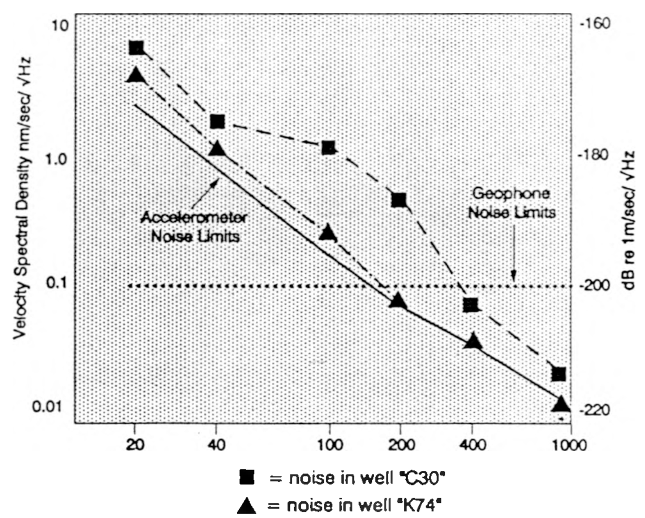
Figure 1



Photograph of prototype
Advanced Borehole Receiver

Figure 2



Seismic noise measured in wells at Texaco Humble Site. Measured using low-noise accelerometers clamped at 1200 ft depth.

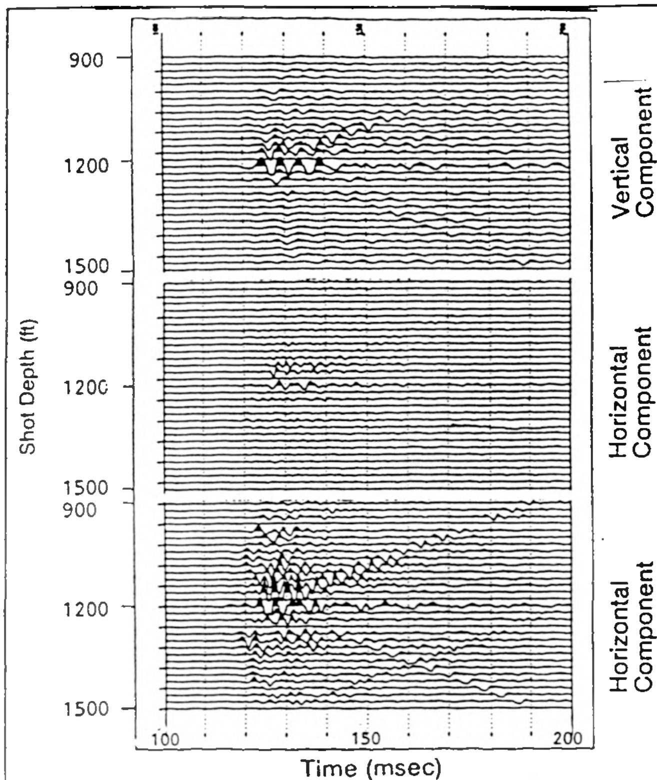


Figure 3: Common-receiver gather obtained from Advanced Borehole Receiver (Accelerometer-Based). Receiver depth is 1200 ft, well-to-well spacing is 815 ft, and fixed display gain is used.

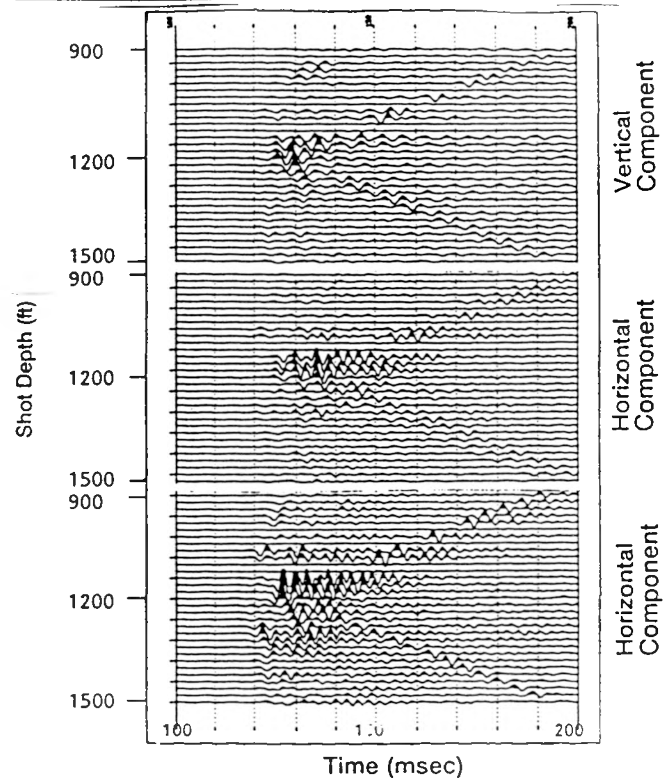


Figure 5: Common-receiver gather obtained from commercial VSP geophone sonde. Sonde depth is 1200 ft, well-to-well spacing is 815 ft, and fixed display is used.

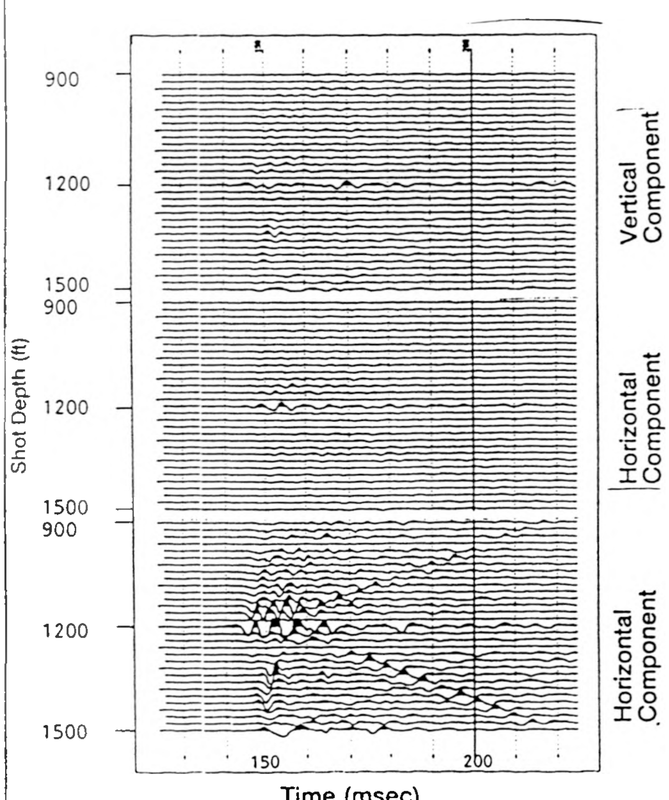


Figure 4: Common-receiver gather obtained from buried and cemented geophones. Geophone depth is 1187 ft, well-to-well spacing is 1215 ft, and fixed display gain is used.

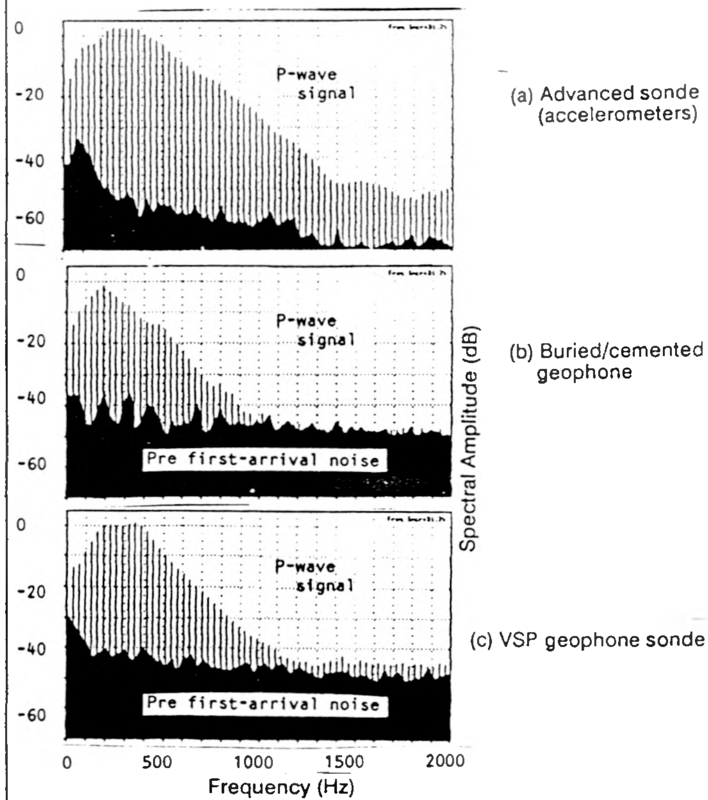


Figure 6: Spectral analysis of common receiver gathers. Both average horizontal-component p-wave spectra and pre-first-arrival noise spectra are shown.