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High-Data-Rate Measurement-While-Drilling System for Very Deep Wells

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Abstract

Measurement-While-Drilling systems presently employing mud pulse telemetry transmit no faster than one or two bits/sec from deep wells containing highly attenuative mud. The reasons – "positive pulsers" create strong signals but large axial flow forces impede fast reciprocation, while "mud sirens" provide high data rates but are severely lacking in signal strength. China National Petroleum Corporation research in MWD telemetry focuses on improved formation evaluation and drilling safety in deep exploration wells. A high-data-rate system providing 10 bits/sec and operable up to 30,000 ft is described, which creates strong source signals by using downhole constructive wave interference in two novel ways. First, telemetry schemes, frequencies and pulser locations in the MWD drill collar are selected for positive wave phasing, and second, sirens-in-series are used to create additive signals without incurring power and erosion penalties. Also, the positions normally occupied by pulsers and turbines are reversed. A systems design approach is undertaken, e.g., strong source signals are augmented with new multiple-transducer surface signal processing methods to remove mudpump noise and signal reflections at both pump and desurger, and mud, bottomhole assembly and drill pipe properties, to the extent possible in practice, are controlled to reduce attenuation. Special scaling methods developed to extrapolate wind tunnel results to real muds flowing at any downhole speed are also given. We also describe the results of detailed acoustic modeling in realistic drilling telemetry channels, and introduce by way of photographs, CNPC's "short wind tunnel" for signal strength, torque, erosion and jamming testing, "very long wind tunnel" (over 1,000 feet) for telemetry evaluation, new siren concept prototype hardware and also typical acoustic test results. Movies demonstrating new test capabilities will be shown in the presentation.

Introduction

The petroleum industry has long acknowledged the need for high-data-rate Measurement-While-Drilling (MWD) mud pulse telemetry in oil and gas exploration. This need is driven by several demand factors: high density logging data collected by more and more sensors, drilling safety for modern managed pressure drilling and real-time decision making, and management of economic risk by enabling more accurate formation evaluation information.

Yet, despite three decades of industry experience, data rates are no better than they were at the inception of mud pulse technology. To be sure, major strides in reliability and other incremental improvements have been made. But siren data rates are still low in deeper wells and positive pulser rates also perform at low levels. Recent claims for data rates exceeding tens of bits/sec are usually offered without detailed basis or description, e.g., the types of mud used and the corresponding hole depths are rarely quoted.

From a business perspective, there is little incentive for existing oil service companies to improve the technology. They monopolize the logging industry, maintain millions of dollars in tool inventory, and understandably prefer the status quo. Then again, high data rates are not easily achieved. Quadrupling a 3 bits/sec signal under a 12 Hz carrier wave, as we will find, involves much more than running a 48 Hz carrier with all else unchanged. Moreover, there exist valid theoretical considerations (via Joukowski's classic formula) that limit the ultimate signal possible from sirens. Very clever mechanical designs for positive pulsers have been proposed and tested. Some offer extremely strong signals, although they are not agile enough for high data rates. But unfortunately, the lack of complementary telemetry schemes and surface signal processing methods renders them hostage to strong reverberations and signal distortions at desurgers.

Fig. 1a - Prototype single-siren tool (assembled).

Fig. 1b - Prototype single-siren tool (disassembled).

One would surmise that good “back of the envelope” planning, from a systems engineering perspective underscoring the importance of both downhole and surface components, is all that is needed, at least in a first pass. Acoustic modeling in itself, while not trivial, is after all a well-developed science in many engineering applications. For example, highly refined theoretical and numerical models are available for industrial ultrasonics, telephonic voice filtering, medical imaging, underwater sonar for submarine detection, sonic boom analysis for aircraft signature minimization, and so on, several of which deal with complicated three-dimensional, short-wave interactions in anisotropic media.

By contrast, MWD mud pulse telemetry can be completely described by a single partial differential equation, in particular, the classical wave equation for long wave acoustics. This is the same equation used, in elementary calculus and physics, to model simple organ pipe resonances and is subject of numerous researches reaching back to the 1700s. Why few MWD designers use wave equation models analytically, or experimentally, by means of wind tunnel analogies implied by the identical forms of the underlying equations, is easily answered: there are no physical analogies that have motivated scientists to even consider models that bear any resemblance to high-data-rate MWD operation. For instance, while it has been possible to model Darcy flows in reservoirs using temperature analogies on flat plates or electrical properties in resistor networks, such approaches have not been possible for the problem at hand.

MWD telemetry basics. Why is mud pulse telemetry so difficult to model? In all industry publications, signal propagation is studied as a piston-driven “high blockage” system where the efficiency is large for positive pulsers and smaller for sirens. The source is located at the very end of the telemetry channel (near the drillbit) because the source-to-bit distance (tens of feet) is considered to be negligible when compared to a typical wavelength (hundreds of feet).

For low frequencies, this assumption is justified. However, the mathematical models developed cannot be used for high-data-rate evaluation, even for the crudest estimates. In practice, a rapidly oscillating positive pulser or rotating siren will create pressure disturbances as drilling mud passes through it that are antisymmetric with respect to source position. For instance, as the valve closes, high pressures are created at the upstream side, while low pressures having identical magnitudes are found on the downstream side. The opposite occurs when the pulser valve opens.

The literature describes only the upgoing signal. However, the equally strong downgoing signal present at the now shorter wavelengths will “reflect at the drillbit” (we will expand on this later) with or without a sign change – and travel through the pulser to add to upgoing waves that are created later in time. Thus, the effect is a “ghost signal” or “shadow” that haunts the intended upgoing signal. But unlike a shadow that simply follows its owner, the use of “phase-shift-keying” (PSK) introduces a certain random element that complicates signal processing: depending on phase, the upgoing and downgoing signals can constructively or destructively interfere. Modeling of such interactions is not difficult in principle since the linearity of the governing equation permits simple superposition methods. However, it is now important to model the source itself: it must create antisymmetric pressure signals and, at the same time, allow up and downgoing waves to transparently pass through it and interfere. It is also necessary to emphasize that wave refraction and reflection methods for very high frequencies (associated with very short wavelengths) are inapplicable. The solution, it turns out, lies in the use of mathematical forcing functions, an application well developed in earthquake engineering and nuclear test detection where seismic waves created by local anomalies travel in multiple directions around the globe only to return and interfere with newer waves.

Wave propagation subtleties are also found at the surface at the standpipe. We have noted that (at least) two sets of signals can be created downhole for a single position-modulated valve action (multiple signals and MWD drill collar reverberations are actually found when area mismatches with the drill pipe are large). These travel to the surface past the standpipe transducers. They reflect not only at the mudpump, but at the desurgers. For high-frequency, low amplitude signals (e.g., those due to existing sirens), desurgers serve their intended purpose and the internal bladders “do not have enough time” to distort signals. On the other hand, for low-frequency, high amplitude signals (e.g., positive pulsers), the effects can be disastrous: a simple square wave can stretch and literally become unrecognizable.

Thus, robust signal processing methods are important. However, most of the schemes in the patent literature amount to no more than common sense recipes that are actually dangerous if implemented. These often suggest “subtracting this, delaying that, adding the two” to create a type of stacked waveform that improves signal-to-noise ratio. The danger lies not in the philosophy but in the lack of scientific rigor: true filtering schemes must be designed around the wave equation and its reflection properties, but few MWD schemes ever are.

Moreover, existing practices demonstrate a lack of understanding with respect to basic wave reflection properties. For example, the mud pump is generally viewed with fear and respect because it is a source of significant noise. It turns out that, with properly designed multiple-transducer signal processing methods, piston induced pressure oscillations can be almost completely removed even if the exact form of their signatures is not known. In addition, theory indicates that a MWD signal will double near a piston interface, which leads to a doubling of the signal-to-noise ratio. This, in fact, has been verified experimentally, a result that has prompted improved strategies for surface transducer placement.

New telemetry approach. A nagging question confronts all designers of high-data-rate mud pulse systems. If sirens are to be the signal generator of choice (because lowered torques enable faster direction reversals), how does one overcome their inherently weaker signal producing properties? The Joukowski formula “$p = \rho Uc$” provides an exact solution from one-dimensional acoustics stating that the pressure induced by a end-mounted piston is equal to the product of fluid density ρ, impact velocity U and sound speed c. It closely describes the acoustic performance of the positive pulser. And because the positive pulser brings the mud column to an almost complete stop – in a way that mud sirens cannot – the Joukowski formula provides the upper limit for siren performance at least as presently implemented.

This understanding prompts us to look for alternatives, both downhole and uphole. We first address downhole physics near the source. We have observed that up and downgoing waves are created at the siren, and that reflection of the latter at the drillbit and their subsequent interaction with "originally upgoing" waves can lead to "random" constructive or destructive wave interference that depends on the information being logged. This is certainly the case with presently used phase-shift-keying which position modulates "at random" the siren rotor.

However, if the rotor is turned at a constant frequency, random wave cancellations are removed. The uncertainty posed by reflections of phase-shifted signals, whose properties depend on nozzle size, wavelength, annular geometry, logging data, and so on, are eliminated in the following sense: a sinusoidal position modulation always creates a similar sinusoidal upgoing pressure wave without "kinks" and possible sign changes. In fact, depending on the location of the source within the MWD drill collar, the geometry of the bottomhole assembly, the transmission frequency and the mud sound speed, the basic wave amplitude can be optimized or de-optimized and controlled with relative ease.

Information in the form of digital 0's and 1's can therefore be transmitted by changes in frequency, that is, through "frequency-shift-keying" (FSK). But, unlike conventional FSK, we select our high frequencies by using only those values that optimize wave amplitude by constructive interference. Neighboring low-amplitude waves need not be obtained by complete valve slowdown, as in conventional PSK. If, say, 60 Hz yields a locally high FSK amplitude, it is possible (and, in fact, we will show) that 55 Hz may yield very low amplitudes, thus fulfilling the basic premise behind FSK. The closeness in frequencies implies that mechanical inertia is not a limiting factor in high data rate because complete stoppage is unnecessary, so that power, torque and electronic control problems are minimal and not a concern.

In order to make constructive interference work, the time delay between the downgoing waves and their reflections, with the newer upgoing waves, must be minimized. This is accomplished by placing the siren as close to the drillbit as possible, with the downhole turbine now positioned at the top of the MWD drill collar. This orientation is disdained by conventional designers because "the turbine may block the signal." However, this concern is unfounded and disproved in all field experiments. This is obvious in retrospect. The "see through area" for turbines is about 50% of the cross-section. If signals can pass through siren rotor-stator combinations with much lower percentages, as they have time and again, they will have little difficulty with turbines.

New Technology Elements

The above discussion introduces the physical ideas that guided our research. An early prototype single-siren tool designed for downhole testing is shown assembled and disassembled in Figs. 1a and 1b. To further refine our approach and understanding of the scientific issues, math models and test facilities were developed to fine-tune engineering details and to obtain "numbers" for actual design hardware and software. We now summarize the technology.

Downhole Source and Signal Optimization

As a focal point for discussion, consider the hypothetical MWD drill collar shown in Fig. 2a. Here, physical dimensions are fixed while siren frequency and position are flexible. Up and downgoing signals (with antisymmetric pressures about the source) will propagate away from the pulser, reflect at the pipe-collar intersection, not to mention the interactions that involve complicated wave transfer through the drillbit and in the borehole annulus.

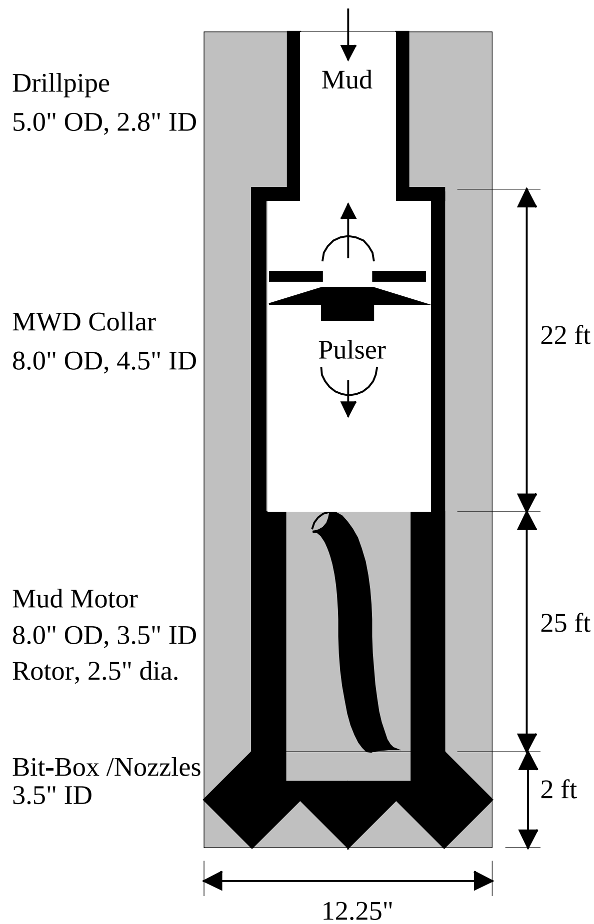


Fig. 2a - Example MWD collar used for siren frequency and source placement optimization analysis.

A six-segment acoustic waveguide math model was formulated and solved, with the following flow elements: drillpipe (satisfying radiation conditions), MWD drill collar, mud motor or other logging sub, bit box, annulus about the drill collar, and finally, annulus about the drillpipe (also satisfying radiation conditions). The "mud motor" in Fig. 2a could well represent a resistivity-at-bit sub. At locations with internal impedance changes, continuity of pressure and mass was invoked. The siren source was modeled as a point dipole using a displacement formulation so that created pressures are antisymmetric. Numerical methods introduce artificial viscosities with unrealistic attenuation and also strong phase errors to traveling waves. Thus, the coupled complex wave equations for all six sections were solved analytically, that is, exactly, to provide uncompromised results.

Calculated results were interesting. Fig. 2b displays the actual signal that travels up the drillpipe (after all complicated waveguide interferences are accounted for) as functions of transmission frequency and source position from the bottom. Here, "Δp" represents the true signal strength due to siren flow, i.e., the differential pressure we later measure in the short wind tunnel. For low frequencies less than 2 Hz, the red zones indicate that optimal wave amplitudes are always found whatever the source location. But at the 12 Hz used in present siren designs, source positioning is crucial: the wrong location can mean poor signal generation and, as can be seen, even "good locations" are bad. These calculations are repeated for upper limits of 50 Hz and 100 Hz in Figs. 2c and 2d. In these diagrams, red means optimal frequency-position pairs for hardware design and signal strength entering the drillpipe. Our objective is p/Δp >> 1 (Δp is separately optimized in hardware and wind tunnel analysis).

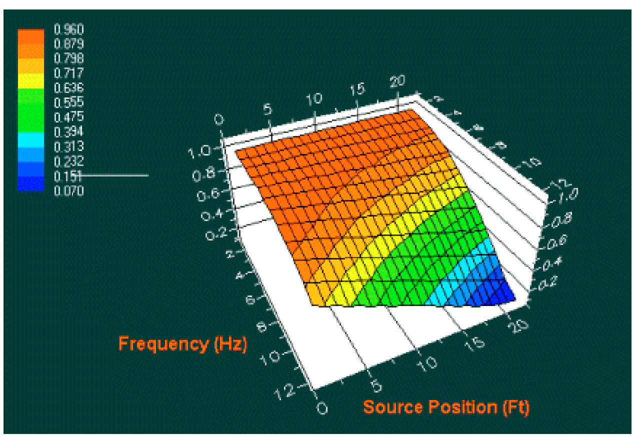


Fig. 2b - Drillpipe p/Δp to 12 Hz.

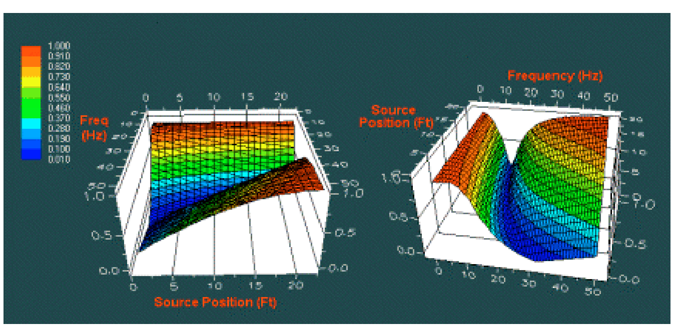


Fig. 2c - Drillpipe p/Δp to 50 Hz.

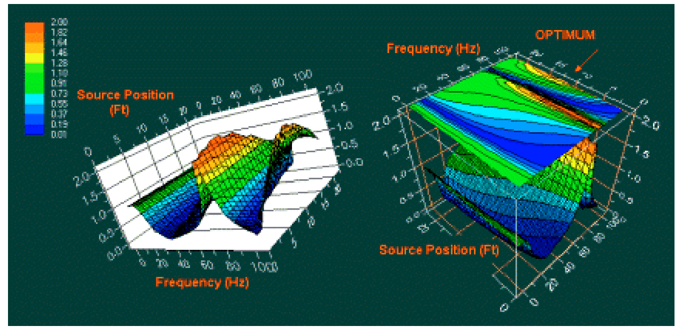


Fig. 2d - Drillpipe p/Δp to 100 Hz.

That present drilling telemetry channels support much higher data rates than siren operations now suggest, e.g., carrier waves exceeding 50 Hz, is confirmed by independent research at www.prescoinc.com/science/drilling.htm. In our designs, we select the frequencies and siren positions, or for sirens-in-tandem, in such a way that high amplitudes are achieved naturally without power or erosion penalties.

Surface Signal Processing and Noise Removal

Downhole signal optimization, of course, has its limits. To complement efforts at the source, surface signal processing and noise removal algorithms must be developed that are robust. Our approach is based on rigorous mathematics from first principles. The classic wave equation states that all "solutions (measured at some point "P" along the standpipe) are superpositions of upgoing "f" and downgoing "g" waves. A differential equation for "f" is constructed. It is then finite differenced in space and time as if a numerical solution were sought. However, it is not. The Δz and Δt in the discretized result are re-interpreted as sensor spacing (in a multiple transducer array) and time delay, whose pressure parameters are easily stored in surface data acquisition systems. The solution for the derivative of the signal was given in U.S. Patent 5,969,638 or Chin (1999). At the time, it was erroneously believed that telemetered data could be retrieved from spatial derivatives but this proved difficult. In recent work, the method was corrected by adding a robust integrator that handles abrupt waveform changes. The successful recovery of "red" results to match "black" inputs, using the seemingly unrelated green and blue inputs, is shown in Figs. 3a and 3b. Mudpump generated noise can be almost completely removed. Experimental validations are given later.

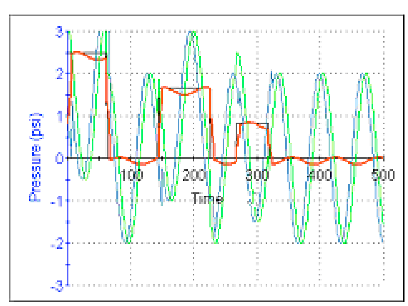


Fig. 3a - Three step pulse recovery from noisy environment.

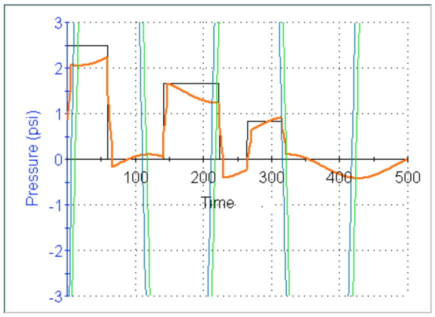


Fig. 3b - Three step pulse recovery (*very* noisy environment).

Pressure, Torque and Erosion Computer Modeling

The mud siren, conceptualized in Fig. 4a, is installed in its own MWD drill collar and consists of two parts, a stationary stator and a rotor that rotates relative to the stator. The rotor periodically blocks the oncoming mud flow as the siren valve opens and closes. Bi-directional pressure pulses are created during rotation. At the very minimum, the cross-sectional flow area is half-blocked by the open siren; at worst, the drill collar is almost completely blocked, leaving a narrow gap (necessary for water hammer pressure signal creation) between stator and rotor faces for fluid passage. This implies high erosion by the sand-laden mud and careful aerodynamic tailoring is needed. Because there are at least a dozen geometric design parameters, testing is expensive and time-consuming. Thus, the computational method in Chin (2004), which solves the three-dimensional Laplace equation for the velocity potential in detail, is used to search for optimal designs. Computed results, displayed for various degrees of valve closure, are shown in Figs. 4b and 4c. Other results include "resistive torque vs angle of closure" important to the design of fast-action rotors. Results are validated and refined by "short wind tunnel" analyses described later.

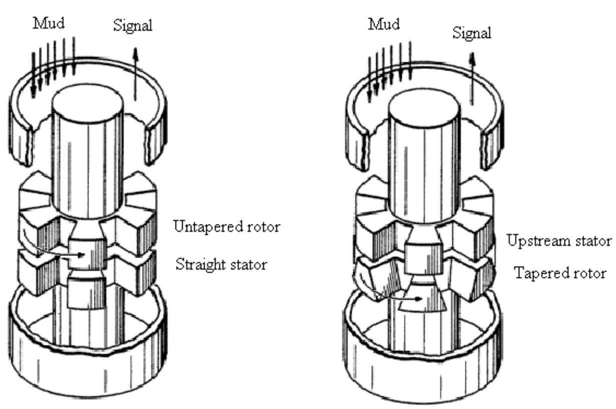


Fig. 4a - Early 1980s "stable closed' siren (left) and improved 1990s "stable-opened" downstream rotor design.

While apparently simple in design, unanticipated flow effects are to be found. The upstream rotor design used in early designs produces numerous operational hazards, the least of them being stoppage of data transmission. When rock debris or sudden jarring occurs, the rotor is known to stop at a closed azimuthal position that completely blocks mud flow. This results in severe tool erosion, extremely high pressures that affect well control, not to mention surface safety issues associated with high pressure buildup at the mudpump. Early solutions addressed the symptoms and not the cause, e.g., mechanical springs that unload the locked rotor, strong permanent magnets that bias special steel assemblies to open positions (thus compromising direction and inclination measurements), and so on. It can be shown that "stable closed" tendencies are a natural aerodynamic consequence of upstream rotor configurations – the rotors tend to close even in clean water. Numerous unsuccessful tests addressing this problem were performed in the 1970s: operational failures associated with jamming valves were catastrophic.

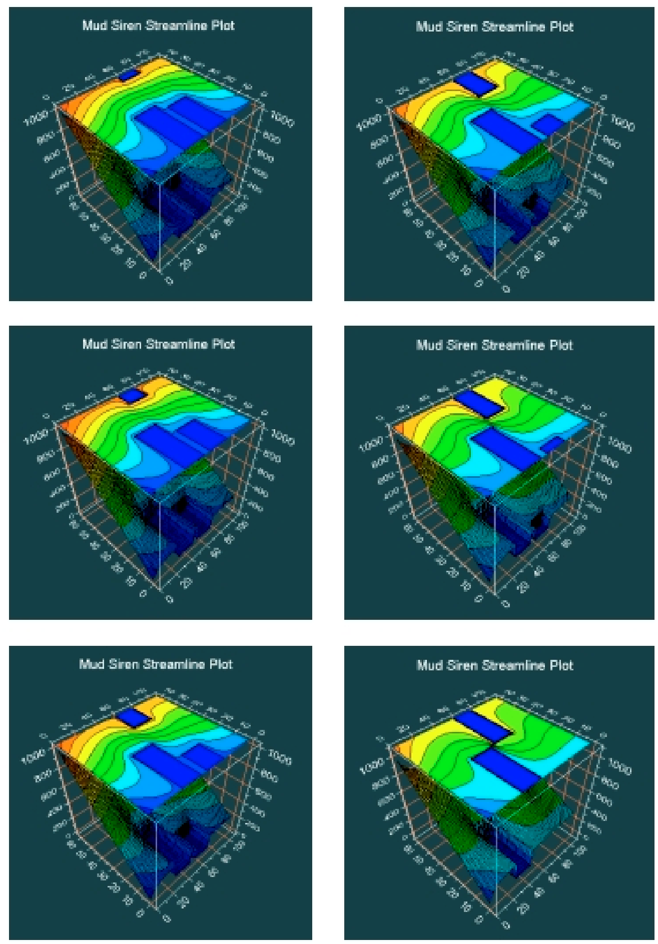


Fig. 4b - Streamline traces for erosion analysis.

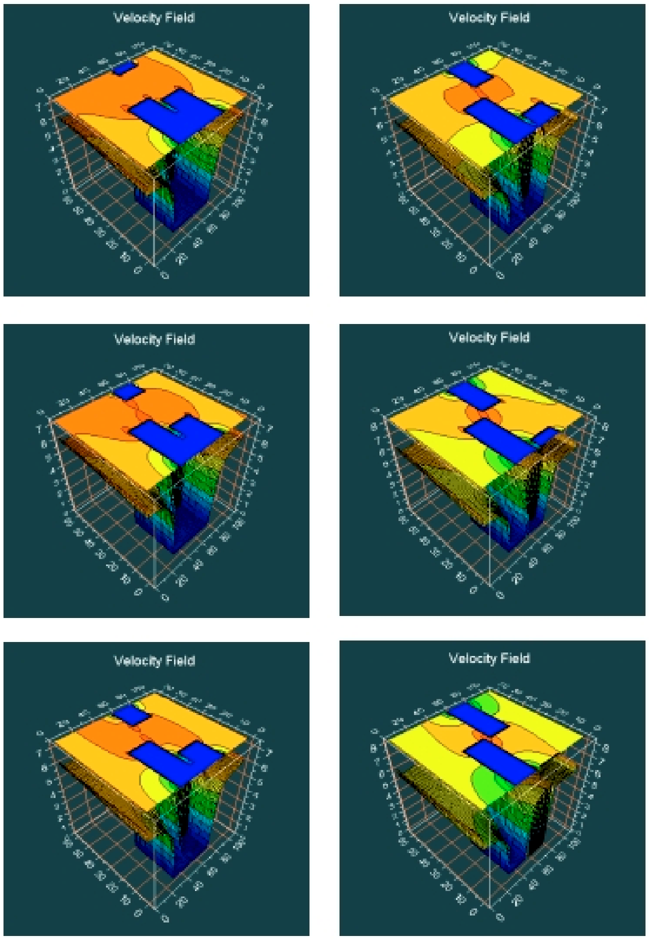


Fig. 4c - Velocities for erosion and pressure analysis.

U. S. Patent 4,785,300 or Chin and Trevino (1988) solved the problem by placing the rotor downstream as indicated in Fig. 4a. The rotor, now "stable open," is augmented with special tapered sides. Torques required to turn, stop or speed up the rotor are much lower than those associated with upstream rotors. From a telemetry standpoint, this means faster position modulation requiring less torque and power, or, much higher data rate. Of course, mechanical considerations are a small part of the problem. Downhole signal enhancement and surface noise removal are equally important, as noted earlier. In our research, all are addressed and fine-tuned to work in concert to provide a fully optimized system.

Wind Tunnel Analysis: Studying New Approaches

While computer models are useful screening tools, they alone are not enough. Gridding effects mask the finest flow details that can be uncovered only through actual testing. The use of wind tunnels in modeling downhole mud flow was first proposed and used by the last author of this paper during his tenure with Schlumberger. Technical details and justification are disclosed in Gavignet, Bradbury and Quetier (1987) who used the method to study flows beneath drill bits nozzles. This counter-intuitive (but correct) approach to modeling drilling muds provides a strategically important alternative to traditional testing and reduces the time and cost of developing new MWD systems.

The CNPC MWD wind tunnel test facility in Beijing consists of two components, a "short flow loop" where principal flow properties and tool characteristics are measured, and a "long loop" (driven by the flow in the short wind tunnel) designed for telemetry concept testing, signal processing and noise removal algorithm evaluation. Field testing procedures and software algorithms for tool properties and surface processing are developed and tested in wind tunnel applications first and then moved effortlessly to the field for evaluation in real mud flows. This provides a degree of efficiency not possible with "mud loop only" approaches.

Our "short wind tunnel," housed at a suburban site, is shown in Fig. 5a. This laboratory location was selected because loud, low-frequency signals are not conducive to office work flow. The created signals are as loud as motorcycle noise and require hearing protection for long duration tests. More remarkable is the fact that internal pipe pressures are several orders of magnitude louder than the waves that escape – this is further multiplied by the (large) ratio of mud to air density, about 800 in the case of water. Thus, careful and precise acoustic signal measurement is required to accurately extrapolate those to mud conditions. Similarly, torques acting on sirens are at least 800 times lower. In fact, air-to-mud torque scaling is simply proportional to the dynamic head "ρU^2" ratio, where U is the oncoming speed. Thus, wind tunnel tests can be run at lower speeds with inexpensive blowers provided a quadratic correction factor is applied for downhole flow extrapolation. The MWD turbine, similarly designed and tested, is not discussed in this paper. Details appear in the forthcoming book <u>MWD Signal Analysis, Optimization and Design</u>, e.g., refer to Chin *et al* (2011).

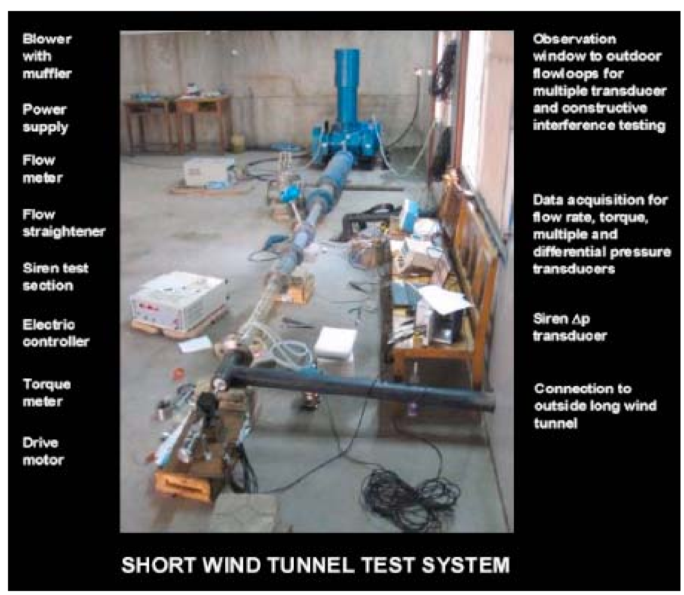


Fig. 5a - Short "hydraulic" wind tunnel system.

In Fig. 5a, a powerful (blue) blower with its own power supply pumps more or less constant flow rate air regardless of siren rotor blockage. A sensitive flow meter is used to record average flow rate. Flow straighteners are used to ensure uniform flow into the siren and to remove downstream swirl for accurate differential pressure measurement. The siren test section deserves special comment. The motion of the rotor is governed by its own electrical controller and is able to effect position-modulated motions as required for telemetry testing.

Siren motion, again, is driven electrically as opposed to hydraulically; azimuthal position, torque and Δp signal strength, i.e., the differential pressure between upstream and downstream sides of the siren, are measured and recorded simultaneously. This data is important to the design of control and feedback loops for actual modulation software. At the bottom of Fig. 5a, a black PVC tube is seen turning to the right into the wall. This emerges outside of the test laboratory, as shown in Fig. 5b, into a long flow section more than 1,000 feet in length. Because the waves are acoustically "long," they reflect minimally at bends, even ninety-degree bends. The long wind tunnel wraps itself about a central facility several times before exhausting into open air. This boundary condition is not, of course, correct in practice; we therefore minimize its effect by reducing signal amplitude, so that end reflections are not likely to compromise data quality.

Also shown in Fig. 5b are "a single transducer" close to the siren test shed (bottom left) and a three-level "multiple transducer array" (bottom right). The former is used to monitor the signal that actually leaves the MWD drill collar, as it depends on constructive or destructive wave interference, while the latter provides data for echo cancellation and noise removal algorithm evaluation. For the simplest schemes, only two transducers are required; three allow redundancies important in the event of data loss or corruption. Additional (recorded) noise associated with real rigsite effects is introduced into the wind tunnel using low frequency woofers.

Numerous siren concepts were evaluated. Several of the sirens shown in this paper are not practical, but were purposely designed to be impractical; a broad range of data was accumulated to enhance our fundamental understanding of rotating flows as they affect signal, torque and erosion.

In our work, we re-evaluated conventional four-lobe siren designs and developed methods that incrementally improve signal strength and reduce torque. Results reinforced the notion that the technology has reached its performance limits. Radically different methods for signal enhancement and minimization of resistive torque were needed.

As noted earlier, constructive wave interference provides "free" signal amplitude without erosion or power penalties. This is cleverly implemented in two ways. First, FSK with alternating high-low amplitudes is used. High amplitudes are achieved by determining optimal frequencies from three-dimensional color plots such as those in Figs. 2b,c,d. Design parameters include sound speed, source position and frequency, MWD collar design, and whenever possible, drillpipe inner diameter an mud density. This information is used in the waveguide model of Fig. 2a and also in a model for non-Newtonian attenuation applicable over the length of the drillpipe.

Fig. 5b - Very long "acoustic" wind tunnel.

Low amplitudes need not be achieved by bringing the rotor to a complete stop. If a high-amplitude is associated with, say 60 Hz, then a useful low-amplitude candidate can be found at, say 55 Hz, as suggested by Figs. 2b,c,d. Thus, FSK can be efficiently achieved while minimizing the effects of mechanical inertia. Rotor torque reduction, while an objective in wind tunnel analysis, is useful, but need not be the main design driver in our approach.

In order to make constructive wave interference work, the siren must be located as close to the most significant bottom reflector, normally the drillbit, as possible (intervening waveguides, e.g., mud motors, resistivity-at-bit subs, and so on, support wave transmission). Thus, the siren is placed beneath the turbine in the MWD collar, in contrast to existing designs. This reduces the time needed for waves to meet and reinforce. Fig. 2a shows a “mud motor.” This aoustic element may, in fact, represent a resistivity-at-bit sub. Calculations show that 10 bits/sec can be accomplished provided this section is approximately fifteen feet in length or less. Tests confirm that long waves pass effortlessly through turbines without reflection. Detailed waveguide analyses suggest that signal gains of 1.5-2.0 are doable. PSK methods, again, are undesirable because they result in wave cancellations and ghost signals that hinder signal processing.

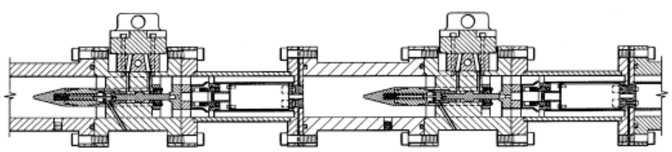


Fig. 5c - A pair of ganged or tandem mud sirens.

Additional signal enhancement is possible using constructive interference of a different nature: multiple sirens arranged in series or in tandem. If the distance between sirens is small and siren apertures are properly phased, signals will be additive. This idea was first proposed in U.S. Patent 5,583,827 or Chin (1996) and a possible design from that publication is reproduced in Fig. 5c. This design, incidentally, is not CNPC’s preferred embodiment.

Two sirens, for instance, mean twice the signal. If the amplification afforded in the previous paragraphs provides a modest signal gain of 1.5, that is, 50%, the net would be a three-fold signal increase more than enough to overcome attenuation at the higher frequencies used. Performance is determined by the single transducer at the bottom left of Fig. 5b which measures the signal leaving the MWD collar. The extent to which constructive wave interference works is found by comparison with the differential pressure Δp taken across the siren (e.g., see Fig. 5h below). This Δp depends on siren geometry, flow rate and rotation only: it is independent of reflections since waves pass through without interaction.

Note that Figs. 2b,c,d suggest that frequencies in the 50-60 Hz range are not unrealistic, a conclusion independently reached at www.prescoinc.com/science/drilling.htm. This use of higher frequencies is also supported by test results from actual flow loop tests with real muds. We stress here that attenuation measurements are subtle since the effects of acoustic nodes and antinodes (which depend on frequency and flow loop boundary conditions) must be properly accounted for. Almost all existing papers on signal attenuation fail to even recognize this problem, let alone correct for it.

Our systems approach to high-data-rate design requires an equal focus on surface systems. As implied earlier, signal strength enhancement must be accompanied by using the most sensitive piezoelectric transducers and robust multiple-transducer echo cancellation methods. The bottom right of Fig. 5b shows a transducer array located far from the test shed. Noise can be introduced by playing back actual field recordings. We have found, to our amusement, that the large firecrackers used at Chinese weddings, e.g., see Fig. 5o, provide a useful source of low-frequency, plane-wave noise when all else is unavailable.

Conventional siren designs are built with four lobes cut along radial lines. Rotating sirens with additional lobes would surely increase frequency or data rate, but large lobe numbers are associated with much lower Δp signals. For this reason, they are not used in designs to the authors’ knowledge. Because constructive interference now enhances our arsenal of tools against attenuation, we have been able to reassess the use of higher lobe numbers. Downhole and uphole telemetry concepts are easily tested in our wind tunnels.

Wind tunnel usage enables a scale of knowledge accumulation, together with cost, time and labor efficiencies not previously possible. Numerous parameters can be evaluated, first by computational models, and then by testing in air. Design parameters are numerous: lobe number, stator and rotor thicknesses, stator-rotor gap, rotor clearance with the collar housing, rotor taper angles, and so on.

Tests are not limited to signal strength. Torque is important, as is the ability to pass lost circulation material – this is assessed by introducing debris at the upstream end of the short wind tunnel and observing the resulting movement. Erosion tendencies are determined by noting the convergence effects of threads glued to solid surfaces – rapid streamline convergence implies high erosion, e.g., see Figs. 4b,c.

Two new parameters were included in our test matrix. The bottom left of Fig. 5d shows a “curved siren” with swept-back blades. Research was performed to determine the degree of harmonic generation associate with constant speed rotations. Since the sound generation process is nonlinear, a rotation rate of ω will not only produce pressure signals with ω, but those with frequencies 2ω, 3ω, 4ω and so on. Higher harmonics are associated with acoustic inefficiencies we wish to eliminate, not to mention surface signal processing problems. Fig. 5e also shows conical flow devices which guide inlet flow into the siren. Their effects on torque and signal were studied. In Figs. 5d-5o, we provide photographs of actual sirens tested and devices used. Many are self-explanatory and are given without further explanation. Improvements to both short and long wind tunnels have since been made in light of our experiences over the past two years.

Fig. 5d - Some sirens tested in wind tunnel.

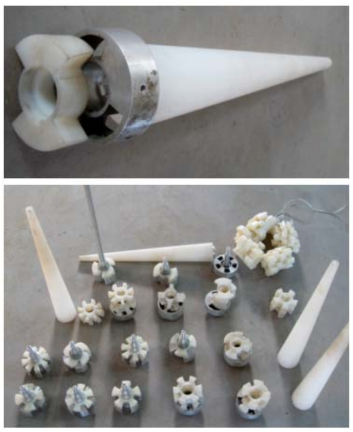


Fig. 5e - Evaluation of hub convergence effects on mud pulse signal strength and torque.

Fig. 5f - Flow straighteners for upstream and downstream use.

Fig. 5g - Flow meter.

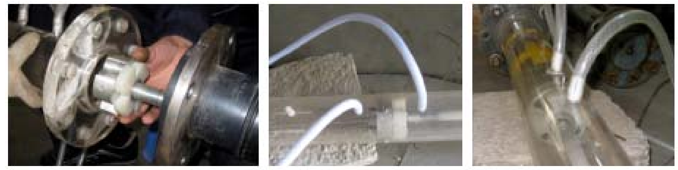


Fig. 5h - Siren test section with differential transducers.

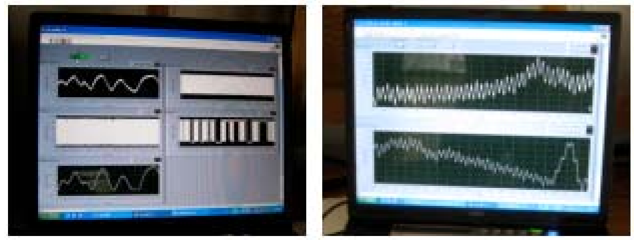


Fig. 5I - Real-time data acquisition and control system.

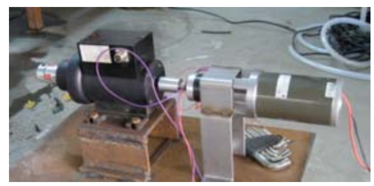


Fig. 5j - Torque, position and rpm counter.

Fig. 5k - Short wind tunnel, "bird's eye" view.

Fig. 5l - Test shed window overlooking long wind tunnel.

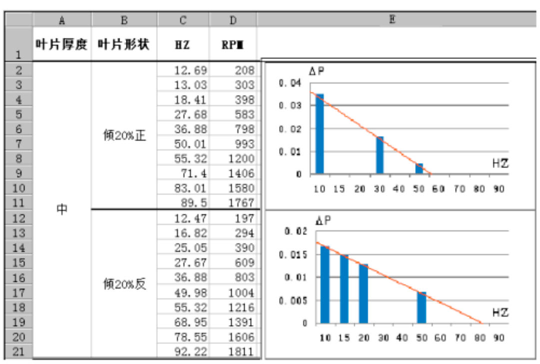
Fig. 5m - Piezoelectric transducer closest to siren for constructive interference and harmonic generation study.

Fig. 5n - Distant multiple transducer array setup.

Fig. 5o - Fireworks, low frequency noise, when all else is unavailable*!*

Example Test Results

Here we highlight some interesting test results. The first pertains to signal strength as a function of rotation rate with flow speed fixed. Early Schlumberger papers claim that Δp's obtained at high frequencies are independent of frequency, i.e., the siren functions as an orifice. We believed otherwise. As the rotor turns, it brings oncoming mud to a halt whatever the frequency. However, the water hammer signal must weaken as rotation rate increases because less time is available for fluid stoppage and rebound. The expected monotonic decrease of Δp with increasing frequency is seen, for instance, in Fig. 6a, where we typically test up to 60 Hz as suggested by Figs. 2b,c,d. The low Δp's associated with existing "siren alone" approaches reinforced our efforts to seek more innovative signal enhancement methods.



	A	B	C	D
1	叶片厚度	叶片形状	HZ	RPM
2	中	倾20%正	12.69	208
3			13.03	303
4			18.41	398
5			27.68	583
6			36.88	798
7			50.01	993
8			55.32	1200
9			71.4	1406
10			83.01	1580
11			89.5	1767
12		倾20%反	12.47	197
13			16.82	294
14			25.05	390
15			27.67	609
16			36.88	803
17			49.98	1004
18			55.32	1216
19			68.95	1391
20			78.55	1606
21			92.22	1811

Fig. 6a - Siren Δp vs ω at with flow rate fixed.

In Fig. 6b, pressure data from the near transducer in Fig. 5m appears at the left, while data from two far transducers in Fig. 5n are shown at the center and right. At the left, the pure sinusoid shows that high-order harmonics have been completely eliminated by the siren design. The two right figures, which contain additive noise, are almost identical. Multiple transducer signal processing in Fig. 6c shows how the red signal is successful extracted from the blue and green to match the black upgoing waveform.

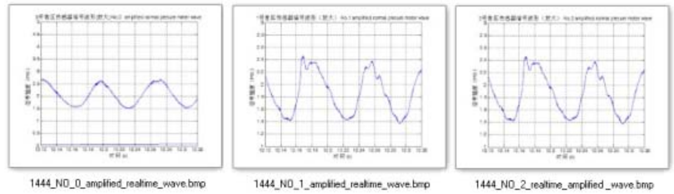


Fig. 6b - Low-frequency (10 Hz) long wind tunnel data.

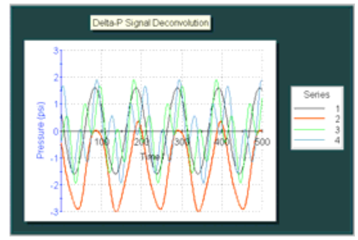


Fig. 6c - Low-frequency (10 Hz) signal recovery.

Complementary results obtained at 45 Hz are shown in Figs. 6d,e. The left diagram of Fig. 6d is clearly not sinusoidal and provides evidence of nonlinear harmonics. Their magnitudes are measured from frequency domain analysis and efforts are made to determine their physical origin. Again, we have successfully extracted the MWD signal from a noisy environment. Our work showed that transducer spacings of 10% of a wavelength sufficed for signal extraction. At the present, not all noise sources are included in our modeling efforts. Vibration and other sound mechanisms will be included in future work.

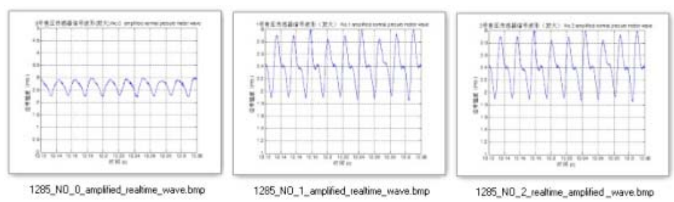


Fig. 6d - High-frequency (45 Hz) long wind tunnel data.

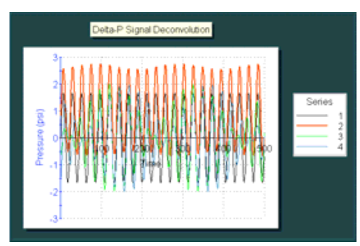


Fig. 6e - High-frequency (45 Hz) signal recovery.

Our experiences with constructive wave interference "at the drillbit" are also worth noting. In U.S. Patent 5,583,827 or Chin (1996), where the use of downhole constructive interference for signal enhancement was first suggested, the published analytical model mistakenly assumed the bit as a solid reflector. In fact, it is known that MWD signals are detectable in the annulus, where their absence is used as an indicator of gas influx. The six-segment waveguide model now used to study typical MWD collars, e.g., see Fig 2a, is more general and does not assume any particular reflection mechanism on an a priori basis. Detailed calculations show that, more often than not, the drillbit acts as an open reflector – attesting to the dangers of "common sense" and visual inspection. This model creates plots similar to Figs. 2b,c,d. The wave characteristics of siren and positive pulsers from present MWD vendors are consistent with those in Figs. 2b.

Conclusions

We have summarized our strategy for high-data-rate mud pulse telemetry and means for developing the technology. Our target objective of 10 bits/sec at 30,000 feet appears to be doable. The signal amplification approach used, together with new surface signal processing techniques, plus the use specially designed tools that are integrated with mud and drillpipe properties, provide a systems oriented process that optimizes data transmission. Needless to say, we have acquired much in our testing program, and we are continually learning from our mistakes and developing new methods to improve the technology.

Prototype (metal) tools have been built, using one or more sirens, and are presently being tested for mechanical integrity and telemetry performance; an example is given in Figs. 1a,b. The very top two photographs in Fig. 5b show the "long wind tunnel" described in this paper, however, it also operates with mud or water using a mud pump and redesigned pulser section (not shown) that is controlled from the test shed at the center of the loop. Real mud laboratory and field tests are in progress and results will be presented at a later date.

Acknowledgments

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