Real Time Half Duplex Communications Wireless Gauge with Downhole Power Monitors Deep Well Gas Production

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The high-temperature, high-pressure system utilizes acoustic waves for communications, and low-power electronics and sensors to acquire and process in real-time data related to production and geological formation parameters.

Monitoring and control of the processes required to produce hydrocarbons constitutes an ongoing industry concern, which is partly because of the expenses and risks associated with the execution of those processes, as well as environmental and safety factors. The ability to provide wireless monitoring of wellbore parameters also has increased completion reliability and decreased completion costs. In an effort to address these issues, Tubel Technologies was funded by the U.S. Department of Energy's National Energy Technology Laboratory to develop a new real-time downhole wireless pressure and temperature gauge for the optimization of natural gas production. This system utilizes the production tubing as the medium for the transmission of the information from downhole to the surface.

The complexity and cost of exploring for oil and gas has increased significantly during the past few years because of intelligent wells, multilaterals and deep gas field developments. New challenges for drilling, completing, producing, intervening in a well, environmental regulations and wide swings in oil prices have changed the role of technology in the oil fields. The industry is relying on technology to affect the costs of exploring for hydrocarbons in the following ways:

- *reduce operating expenses* by automating the processes used to explore and produce hydrocarbons, reducing the frequency of unplanned intervention, and improving information and knowledge management to decrease operating inefficiencies;
- *increase net present value* by providing systems that enhance the recovery of hydrocarbons from reservoirs. The new technologies improve production techniques to delay and/or reduce the production of water from downhole; and
- *reduce capital expenditures* by creating processes that will decrease the number of wells drilled and reduce the number of surface facilities required. The surface equipment requirements to handle increasingly larger quantities of hydrocarbons at these facilities should also decrease with the implementation of new technologies.

New processes for drilling, completion, production, artificial lift and reservoir management have been created by advancements in technology in fields such as high temperature sensory, downhole navigation systems, composite materials, computer processing speed and power, software management, knowledge gathering and processing, communications and power management. Horizontal drilling and new fracture techniques have allowed operators to produce hydrocarbons profitably from areas uneconomical just a few years ago.

Sensor technology in conjunction with data communications techniques provide on-demand access to the information necessary to optimize hydrocarbon production levels and achieve costs goals. Surface and downhole sensors are changing the way hydrocarbons are produced by optimizing production from downhole, supporting and extending the life of artificial lift systems and providing information used to update reservoir and production models.

A new technology that combines sensors with wireless telemetry provides the operators with new versatility and capability to place sensors in areas of the wellbore that were prohibitive because of technical difficulties and/or economic justification. The ability to communicate in and out of the wellbore using wireless systems can increase the reliability of the production system and decrease the amount of time required for the installation of the completion hardware in the wellbore. The elimination of cables, clamps, external pressure and temperature sensors, as well as splices on the cable that can fail inside the wellbore, provides a significant advantage to existing gauge technologies.

The wireless wellbore digital data communications and sensing system provides the capability to communicate through the production tubing using stress waves to transmit and receive digital data and commands

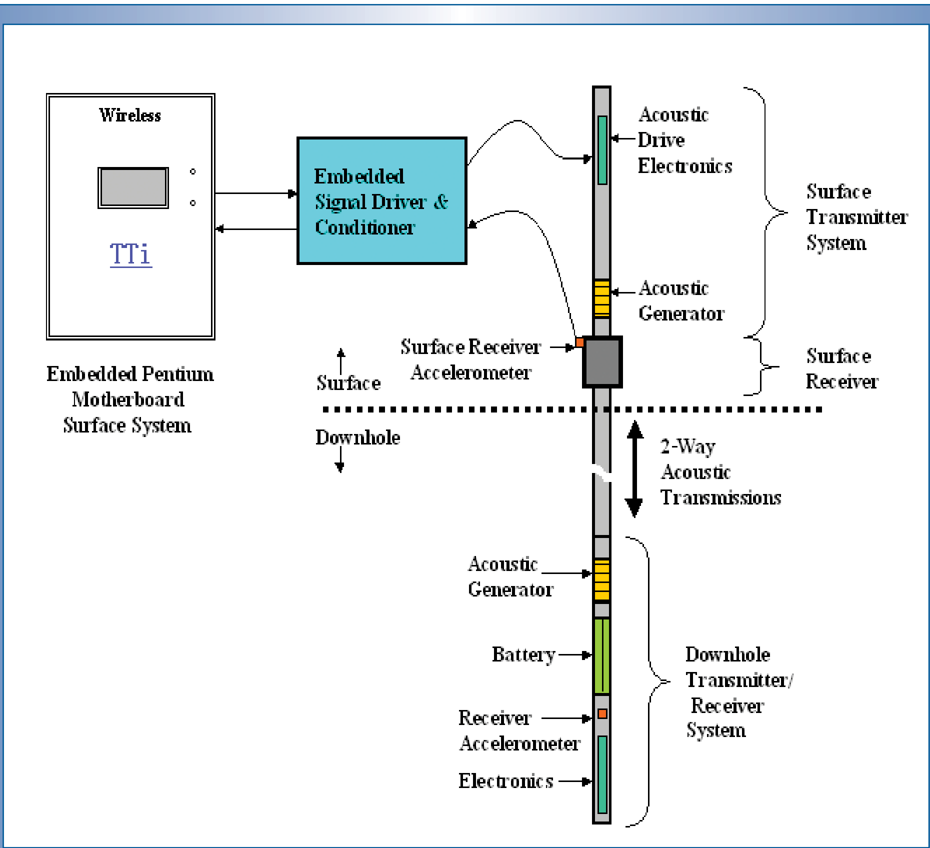


Figure 1. A two-way communication wireless gauge well configuration block diagram is shown above.

inside the wellbore. The system provides information from inside the wellbore that is transmitted at intervals determined by the customer and programmed before the tool is inserted in the well. The downhole system is composed of the wireless transmission hardware, microprocessor system for data acquisition and power management, pressure and temperature gauges and a power generation unit. The surface system is composed of a detection and transmission module and a surface supervisory control and acquisition box for data acquisition and processing. Figure 1 shows a block diagram of the two-way communication system.

The wireless gauge hardware creates the acoustic signals from electrical pulses generated by the electronics system after the sensor information is digitized. The acoustic waves are coupled to the production pipe minimizing the amount of energy losses having a tight fit between the acoustic generator and the production pipe. The waves traveling up the pipe to the surface are immune to losses related to fluid coupling and tubing threads.

The electronics system provides the process control, data acquisition, data processing, data encoding, command decoding and operator interface. The system provides a power saver mode while in the wellbore to maximize the downhole power efficiency. The electronics sample and digitize the information from the gauges at specific time intervals programmed before the tool is deployed inside the wellbore. The data is processed and encoded for transmission to minimize the number of bits of data required to be sent to the surface. The microprocessor then generates the electrical pulses used to drive the acoustic generator to produce the information related to the pressure and temperature data obtained inside the wellbore. Upon completion of the information transmission to the surface, the processor places the tool in a power saver mode until it is awoken to perform the data acquisition tasks again. The system also can receive commands from the surface, and an acoustic detector wakes the processor for the data acquisition and process.

The sensors are composed of silicon on sapphire pressure gauges and thermocouples for sensing temperature. The sapphire gauges provide high-resolution pressure measurements on the annulus and tubing while the thermocouples inside the pressure assembly measure temperature for pressure compensation and well monitoring. This new sapphire technology eliminates the well fluid coupling requirements to maintain the sensor assembly free of well contamination. The sapphire is in constant contact with the wellbore fluids to provide a more accurate measurement of the pressure. Higher stability also is a major advantage of the sapphire gauges to strain gauges, as the gauges are built into the tool eliminating any outside connections.

The surface system provides data acquisition, processing, storage and display capabilities for the data received from inside the wellbore. The surface system is composed of three modules:

- *surface data detection transmission on tubing*—A surface module attached to the wellhead or just below the surface is used to detect the transmitted downhole signal. It converts the signal from an acoustic wave into digital electrical pulses transferred via surface cable to the data processing module. It also converts electrical pulses into acoustic commands;
- *surface processing module*—This provides the data acquisition, processing, display and interfaces to a pump controller or a computer. The data received from the acquisition module is conditioned and pre-processed to eliminate noise. The data is next processed in the time

domain to obtain the actual parameter values gathered by the sensors inside the wellbore. The information is converted into 4-miliamp to 20-miliamp analog signals to be transmitted to a pump controller or recorder. The information also is converted into Modbus protocol data stream to be transferred to other computer systems; and

- *a personal computer* (PC) interfaces with the surface-processing module to obtain the downhole information. A software package for the PC processes the data for viewing the information in a graphical mode or in a tabulated format.

The wireless communications tool does not disrupt the flow of production fluids because it provides full tubing inside diameter. Since the signals are carried by stress waves in the production tubing, the data is virtually unaffected by the well fluid.

There are four issues that affect the system performance:

- *the strength of the data signal that can be produced*—The higher the energy generated inside the tool because of voltage levels and transmitter/tubing coupling, the longer the distance between the transmitter and receiver modules;
- *the attenuation of the transmission path*—The pipe being in contact with casing over extended lengths affects the wellbore signal path. The tubing has to be continuous from the tool to the surface for the signal to reach the surface detector;
- *the allowable signal- to-noise level for data acquisition*—The signal levels have to be in the micro g's (g is equal to the acceleration of gravity at 9.81m/second^2) for the surface system to detect the acoustic data on the tubing. The downhole tool power level has to be designed to assure the acoustic signal will have a level high enough to be detected by the surface hardware; and
- *the noise environment of the well*—The signal-to-noise ratio (SNR) in the passband of the surface system's filters is critical for communication. The SNR must be maintained above a certain level for the packets to be correctly decoded by the surface system.

The advantages of an acoustic wireless gauge can be compounded if the capability for two-way communications is added. Communication parameters such as data refresh rates and sensor selection must be set at the surface before deployment and cannot be modified until the gauge is recovered. The ability of a gauge to receive surface communication removes this limitation, since a command set allowing communication parameter modification can be implemented. The first command to have been implemented was an asynchronous request for a sensor reading. This significantly reduces power consumption, since sensor readings are taken only when required. Another potential command includes changing communication parameters such as transmission frequency. This is useful because each well has a unique acoustic profile and ambient noise environment. Modifying the transmission frequency in use allows communication even in a dynamic noise environment. Selecting a transmission frequency also allows multiple gauges to be deployed in a well with a single surface transceiver for the entire gauge set.

Half-duplex surface system

The major subsystems include an acoustic transmitter, an acoustic receiver, an amplifier, an analog to digital converter and a Pentium-based processor board.

The acoustic receiver was implemented as a 5-g accelerometer along with the required drive circuitry. The output from the accelerometer was fed into a variable gain amplifier stage, where it was amplified by about 2000. The exact gain provided by the amplifier was determined by the intensity of the signal received from the half duplex gauge. The gain was chosen to maximize the SNR without saturating the amplifier.

The output of the amplifier stage was fed into the analog digital converter (ADC), which was operated at a sampling frequency of 11,025 Hz with 16-bit resolution. Decoding software, which is user-configurable and not highly sensitive to absolute gain level, processed the data acquired from the ADC.

The decoding software was implemented as a set of interlocking finite state machines, each of which handles a different level of the communication protocol. For example, there is a separate state machine for bit detection, received packet formation and received packet validation. Bit detection is accomplished by a time-frequency transform, accompanied by energy level hysteresis for noise immunity and energy level debouncing to avoid detection of false bits. Packets are constructed by concatenating a fixed number of bits. Packet validation occurs by throwing away any packet that does not conform to the defined packet structure.

For communication in the opposite direction, there is another set of software modules responsible for encoding packets. Again, interlocking state machines were used to generate packets, with each protocol layer represented by a separate state machine. Some of the more important transmission machines include bit generation and transmitted packet formation.

The acoustic transmitter consists of an electronic driver module, a transformer and an acoustic generator. These components are identical to those in the half-duplex downhole gauge. Since power consumption is not an issue at the surface, transmitting at the maximum level of output can optimize transmission.

Half-duplex wireless gauge

Surface panel application development is relatively straightforward, since, for all practical

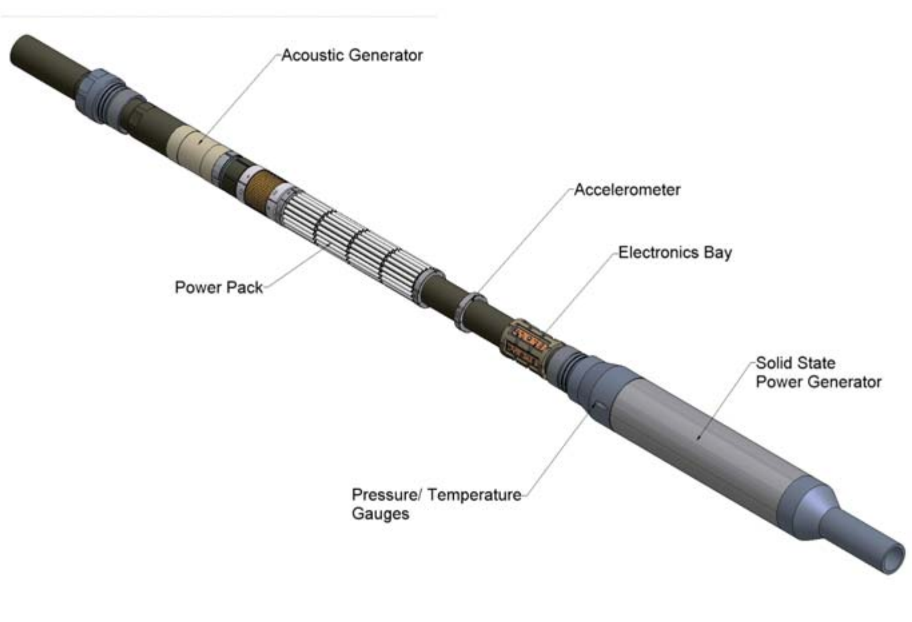


Figure 2. The above graphic shows a half-duplex communications self-powered downhole wireless gauge.

purposes, there are unlimited resources in terms of memory, processing power, storage, etc. Downhole application development has none of these advantages. Instead, the downhole tool is limited in memory, sampling resolution and especially processing power.

The processor has eight integrated A/D converters capable of 10-bit resolution, which is a limiting factor in tone detection, since it corresponds to a dynamic range of only 60 dB. The surface system used had a 16-bit A/D with a corresponding dynamic range of more than 96 dB.

The processor is being operated as a microcontroller, which means the internal random access memory (RAM) is being used. There are 1,536 bytes of internal RAM, which limits the size of the sampled data array that can be processed. Since sampling must continue during processing, two data buffers are required: one for signal processing, and one for current data acquisition. This can be compared with the RAM available to the surface system, 512 MB.

Figure 2 shows the schematic of the half-duplex wireless gauge.

Downhole power generator

The downhole power generator was designed to be part of the wireless gauge mandrel to reduce the length and cost and increase the system reliability. The power generator was designed to provide a direct action between the wellbore and power generator hardware. The new power generator design is solid state and obtains energy from hydrocarbon flow as well as wellbore vibration. The power generator was designed as with a modular approach, where multiple generators can be stacked as part of the downhole wireless gauge based on the amount of energy required in the well. The amount of energy that can be generated is related to flow and vibration levels in the wellbore.

Signal detection algorithms

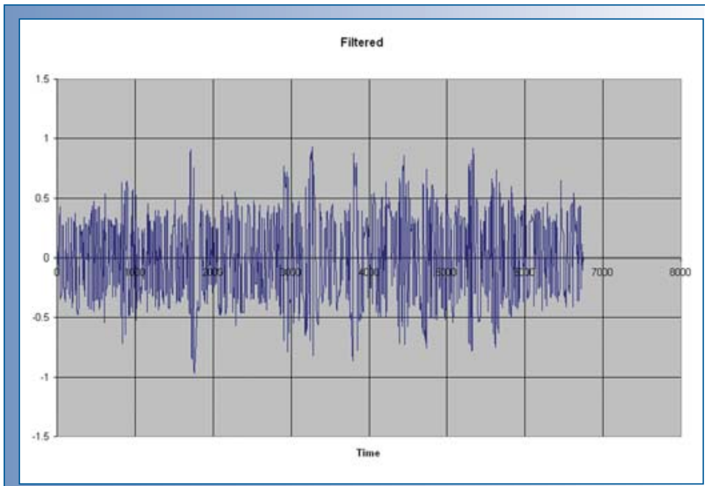
Since many off-the-shelf implementations exist for the fast Fourier transform (FFT), the first time-frequency transform tested was the FFT. Most of these implementations are floating point, since rarely do applications have the resource limitations listed above or are required to operate in real time. For development speed, one of these implementations was modified for our application.

The frequency of the signal for the purpose of this article determined the sampling rate, which combined with the duration of the signal led to the bin size. The result of the testing showed the algorithm was highly successful in signal detection. Unfortunately, processing a single bin took more than a second, which exceeds the available time.

To reduce the processing time, the floating point software was converted to a fixed point. Although it reduced processing time significantly, bin processing still exceeded the maximum acceptable. The next step in increasing efficiency was to truncate the 10-bit input from the A/D converter to eight bits so single-cycle multiplications could be used. The maximum acceptable processing time was still exceeded. No further efficiencies could be identified, so algorithm testing switched to Goertzel's algorithm. Although this does not provide information about the entire spectrum, it is highly efficient for energy detection at a limited number of discrete tones.

Documentation on Goertzel's Algorithm is almost universally based on a floating point implementation. Therefore, development started using a floating point implementation. The first attempt was made using the full 10-bit output of the A/D. Testing showed the speed of processing was still insufficient. To reduce processing time, phase information was ignored. By doing this and discarding the two least significant bits, processing time was reduced to 15 milliseconds, which were significantly below the requirement, so further optimization was not needed. Just as in the case of the FFT, the next step would have been to move to a fixed point implementation.

The integration interval, which also was the basic mechanism for advance in the bit detection finite state machine, was deter-



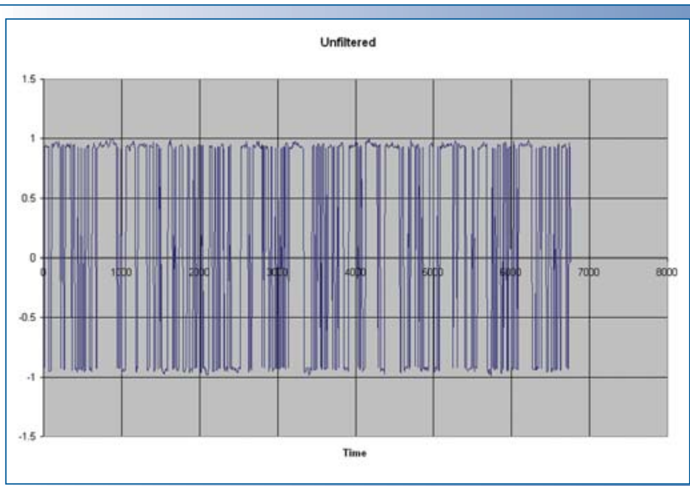


Figure 3 (left) shows the filtered data and Figure 4 (right) shows the digitized unfiltered data.

mined by the bit design and packet structure.

The other input to the finite state machine (FSM) was a threshold energy determined experimentally. Exceeding that energy would allow the FSM to advance, while energy detection below the threshold would lead to a reset of the state machine.

For noise immunity, threshold levels for bit detection and bit absence were used.

Experimental results

On April 26, the prototype gauge and surface system was tested for surface to downhole communications at the north test well at the Carrollton, Texas, facility of Halliburton. The wireless gauge was deployed in the test well using 3½-in. diameter tubing above the gauge. The downhole to surface communications for the wireless gauge had been prreviously tested in a horizontal well at 6,900ft where the completion hardware included packers, sliding sleeve, gas lift valve and safety valve located above the wireless gauge. The system was deployed at 200ft in the well, and the transmitter from the surface to downhole was attached to the top of the tubing string at the surface slips. The surface to downhole transmitter module was connected to the processing panel and the PC. A command was initiated from the computer to request data from the tool. The transmitter transferred the information into the wellbore using acoustic waves. The downhole tool received the acoustic information, processed it and responded to the request for data providing annulus pressure readings.

The downhole module was lowered to 500ft in the wellbore. The surface module was re-attached to the top of the tubing string and a command was transmitted in the wellbore. The downhole acoustic receiver was not capable of detecting the downhole information because of a high software threshold level implemented in the tool. A software modification was performed to lower the threshold to allow the downhole tool to receive smaller signals consequently being able to go deeper in wellbores. With this modification, the downhole wireless gauge should be able to detect acoustic signals transmitted from the surface at distances up to 12,000ft. The wireless gauge evaluation and tests will continue with another well test scheduled for July.

Conclusion

A new downhole gauge has been developed for monitoring deep well gas production. The system is self-sufficient where power, sensors and communications are built as one tool. The new system can provide pressure and temperature measurements and generate power inside the well. A power storage module is capable of capturing, conditioning and storing the energy generated for utilization during the data transmission to the surface. A surface to downhole communications module also was developed to transmit information to the downhole gauge to provide the ability to change data rates or ask for data in a master-slave configuration. A new digital signal-processing module for the downhole tool has been proven to work in the wellbore environment and capable of differentiating signal from noise. It also is capable of detecting and processing the commands issued at the surface.

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