1. INTRODUCTION OF THE DATA TRANSMISSION TECHNOLOGY OF MWD

Measurement While Drilling (MWD) is an advanced technique in directional drilling, which can measure the information about the bottom of the drill hole without interruption, and send the information to the surface instantly. With the development of technology, modern drilling measurement has been developed into Logging While Drilling (LWD), which can not only monitor directional drilling, but also carry out comprehensive logging.

The main difference between MWD and conventional logging or storage logging lies in the real-time data transmission. The logging curve is obtained in the case of a slight invasion or even no invasion of the ground fluid, so it is closer to the real situation of the ground.

Through the field analysis, processing and interpretation of the data underground, it is helpful to evaluate the comprehensive strata in time, and to adjust the drilling trajectory. Therefore, signal transmission is a key link of MWD technology, and it is also a "bottleneck" that restricts the development of MWD technology. The three major international petroleum technology services companies (*i.e.* Schlumberger, Halliburton, and Baker Hughes), represent the front of the world's logging technology. For ground and underground communication systems, their work is closely related to the two aspects of wired transmission and wireless transmission. Compared with the foreign technology, China is still in the stage of introducing and digesting foreign MWD technology. Some units and research institutions have successfully developed a MWD system, using wireless mud pressure wave based on a positive pulse. But we should speed up the MWD research of other communication methods so as to eliminate the long-term monopoly of MWD technology. This chapter gives a brief analysis of the two series of MWD data transmission principles, characteristics and development, and points out the future research priorities and directions.

1.1. Wired Transmission

The wired transmission mode includes cable transmission, special drill pipe transmission, and optical fiber transmission [1].

1.1.1. Cable Transmission

In cable transmission, the signal goes down the inside of the drill pipe to the electrical conductor, which is similar to the armored cable in cable logging. With the deepening of drilling, cables and instruments must be pulled upward to connect drill pipes. The other way is to sleeve the cable into the inner hole of the drill pipe in advance.

Two methods are used to transmit data. One is to add a closing device on the side of the drill string. The device is similar to a three-way whose upper and lower passages are connected to the drill string, and its lateral passage can move the cable line of the directional measuring instrument inside the drill string to the outside. The cable is attached to the outer wall of the drill string [2]. This method is effective when the drill string does not rotate during drilling, but the abrasion and extrusion of cables should be prevented. Another way is to store an extra length of cable on the reel inside the drill pipe. The motor locking pin installed in the system can temporarily interrupt the data transmission when adding another drill pipe, and the whole cable must be recovered before tripping out.

The second way is to use a coaxial conductor to transmit signals. It adopts coaxial wiring mode and has a copper tube centered conductor with insulating layer outside [3]. After inserting the conductor into the drill pipe, the liquid pressure underground will expand the conductor to seal it tightly within the inner wall of the drill pipe. When the drill string is connected, the signal can be transmitted between the drill pipes to form a high-speed bidirectional information network. The method has been applied successfully in the test wells, and its maximum transmission rate can reach 2 Mbit/s.

The advantage of cable transmission is that the transmission rate is high and bi-directional. At the same time, power can be provided directly from the ground to the downhole sensor, without additional power source at the bottom of the well. The disadvantage is that the producing process is relatively complex and often affects the normal drilling process.

1.1.2. Special Drill Pipe Transmission

The method is to insert a conductor into the drill pipe. Special connections inside the joint allow the drill string to conduct electricity. The sensor is fixed in a drill collar. The armoured cable (or jumper wire) connects the drill collar to the bottom of the drill pipe [4]. An insulated slip ring is installed at the top of the Kelly bar and the ring is connected to the ground equipment.

The key of this transmission method is the drill pipe joint, which can be designed in different methods including induction, wet joint, Holzer effect sensor and wire butt joint. A telemetry drill pipe system of sensing joint developed by Grant Predi-co, a company in the United States, has an induction coil at both ends of the drill string. The coils transmit data to adjacent joint coils in turn with a transmission rate of up to 1 Mbit/s. So it is not necessary to connect or disconnect the wire connector on the drill pipe when screwing in and screwing out the drill pipe. The intelligent drill pipe uses copper wire as the conductor, and the transmission power is determined by the underground hardware power consumption.

The advantages of the special drill pipe transmission are the fast data transmission speed and the simple two-way communication. The disadvantage is that the special drill pipe is a must and the cost is high. As it is difficult to obtain continuous circuit at the joint, the reliability is poor, and it is difficult to transmit the power to the down-hole.

Since the commercialization of IntelliServ, a system of special wired drill pipe (SWD) developed by NOV (National Oilwell Varc), it has been used in more than 120 wells in different countries and regions, including offshore drilling, vertical wells, deviated wells and horizontal wells. The system is mainly composed of interface device, electronic parts, wired drill pipe, drill string and top drive rotary joint. The interface device is used to connect the MWD instrument for two-way data communication. Electronic components are used for signal enhancement and can measure pressure and temperature. Wired drill pipe is the core of the system, which communicates with the induction coil at a high speed. The coil is connected to a high speed and high intensity data cable fixed in the pipe joint, and the signal from the bottom of the drill pipe can be induced without direct contact. The top drive rotary joint can replace the protective connector so that the system can switch between the rotation and the stop. This system can provide high quality data transmission at a speed of 57 kbit/s. By measuring the parameters including well diameter, torque, pressure, temperature, strain, stress and vibration rate, the stability evaluation of the shaft wall can be conducted and the well distribution is accurate. At the same time, it is helpful to the analysis and evaluation of borehole vibration control, ring pressure monitoring, underground instrument control and formation pressure test. In addition, it can quickly update the formation model to reduce the operation risk, speed up the hole trajectory adjustment, monitor the state and performance of the instrument in real time, improve the drilling efficiency, and improve the economy of the project by reducing the non-production time.

In Visund, an oil and gas field of Norway, by taking the advantage of the high frequency signal transmission of the IntelliServ system, the full borehole diameter data is transmitted to the ground in real time. It not only helped the operator to determine whether the reamer worked normally, but also avoided the unnecessary drilling for adjusting the rotating guide system or investigating the borehole expansion, and saved 2 days for the operating company, compared with the traditional method.

NOV has made the following improvements to the IntelliServ transmission network to improve its stability and transmission efficiency, which formed a new generation of network—IntelliServ2:

1) NetCon (the network control module) has been embedded in a very small stainless steel casing. NOV has rewritten the whole software interaction module, simplified the interaction way, used a simpler top-to-bottom way to transmit data, and the touch plane has been simpler and easier to operate;

2) The data cable was improved and wrapped in the chromium nickel alloy, which was more resistant to corrosion and wear;

3) DataLink was redesigned to increase the stability and performance of transmission network;

4) The sensing coil, which was made of more durable material and protected by the thread, was embedded into the double shoulders drill pipe. The sensor line can be replaced and reused, so the maintenance cost can be reduced by 80%.

The data transmission system of IntelliServ2 brings higher efficiency, stability and reliability to customers, and reduces work time at the same time. IntelliServ2's wired drill pipe (WDP) performs better in some wells. A developer of Bakken, a block in US, used IntelliServ2 to transmit data of 16 wells, through the WDP telemetry system, downhole data can be obtained to drive the operation of ground drill, making it more efficient and safe (**Figure 1-1**).

In this case of Bakken, the operator drilled 16 Wells in four different locations through WDP. The hole size was 8.75 in, the vertical depth was 762 m, the depth was 3537 m, and the total penetration was 43,586 m. It is impressive that during the operation, IntelliServ2 has monitored the equipment for over 99.6% of the time, a total of more than 1451 hours. Compared with the previous drilling system, the combination of IntelliServ2 and WDP greatly optimizes the drilling operation. The 13 Wells in the project were drilled in blocks that had never been operated in the previous three years, so the operation was difficult. After using automated services, the drilling time decreased by 25% and the vertical drilling time decreased by 31%. Although the operations time spent on each well was different, it was true that it saved much time.

In addition to reducing operating hours, the WDP's real-time data transmission is capable of detecting downhole conditions more quickly so that the operators can adjust the drilling program more quickly. At the same time, the combination of drill collar, SoftSpeed software and WDP reduces risks of drag and slippage in the vertical section of the drill pipe. TrueDrill software shows that WDP can effectively increase the drilling rate (ROP) by exerting force on the drill bit, which exceeds the ROP limit of conventional drilling operation, and the drilling operation is more stable.

Figure 1-1. Intelliserv2 of NOV.

In Russia, the cable is used in each single drill pipe, and the signal is transmitted by plugging at the joint of the drill pipe. IFP, a French company, has adopted a lip sealed electric drill pipe, which has been successfully applied to shallow wells of 1000 m. However, the application of this technology in our country is still blank.

1.1.3. Optical Fiber Transmission

We can insert a cheap optical fiber with a simple protective layer into the well. The length of the fiber is the same as the drill string, from the bottom hole assembly (BHA) up to the ground. The light passing the optical device can circulate between the ground and the BHA underground along the shaft. The Sandia National Laboratories of US has developed and experimented with the optical fiber telemetry system for MWD. The fiber-optic cable is thin, and low in cost, which can be used for a short period of time, and is eventually worn and washed away by the drilling mud. In tests at the American natural gas institute, the optical fiber could reach a depth of 915 m. Optical fiber telemetry can transmit data at a rate of about 1 Mbit/s, which is about 5 orders of magnitude faster than other commercial wireless technology.

1.2. Wireless Transmission

The transmission channels of wireless MWD can be divided into four types: mud pulse, electromagnetic wave, sound wave and mixed measurement. Compared with the mixed measurement, which is not very mature at present, the mud pulse transmission and electromagnetic wave transmission have been applied a lot in practice, and the mud pulse mode is most commonly used.

1.2.1. Mud Pulse Transmission

As the most widely used method of wireless transmission of MWDS field, mud pulse mode can transmit information through the mud flow. Without insulation cable and special drill pipe, the operating cost is greatly reduced, but because of its low bandwidth, it restricts the amount of data transmitted to the surface, and its data transmission rate is slow due to the influence of pulse and regulating speed. In addition, the data compression rate determines the resolution of logging data, especially in image logging, and the low bandwidth of mud impulse has great influence on the accurate transmission of borehole image, reducing the value of the real-time data. Therefore, in order to obtain accurate images, the appropriate data compression ratio must be selected to optimize the bandwidth.

Mud pulse [5] [6] [7] mode of MWD system conveys downhole information by means of hydraulic communication channel. The hydraulic communication channel is a closed system consisting of drilling fluid from the wellhead to the downhole. Through the hollow drill string, the drilling fluid is pumped into the downhole engine to cool and lubricate the drill bit, flows into the bottom of the well through the drill hole, and then carries the debris from the circular space between the drill string and the borehole to the mud pool. The rock debris are separated from the drilling fluid in the mud pool, and the purified drilling fluid is injected into the drill string again, forming the flowing cycle of drilling fluid.

At present there are 3 ways of signal transmission with drilling fluid as the medium [8] [9] [10] [11]: positive pulse, negative pulse and continuous wave.

The Negative Pulse Generator: the transmitter is composed of a discharge valve. When the valve opens, part of the drilling fluid flows from the drill string to the annulus. So opening and closing the valve will cause a series of negative pulses generated by the pressure wave in the tube and transmit the data to the ground. From the mechanism of signal generation, it belongs to the discharge signal generator (see **Figure 1-2**).

Positive Pulse Signal Generator: there is a throttle valve in the downhole signal generator controlled by the hydraulic regulator. When the valve opens, the transient compression of the drilling fluid flowing through the drill string leads to an increase

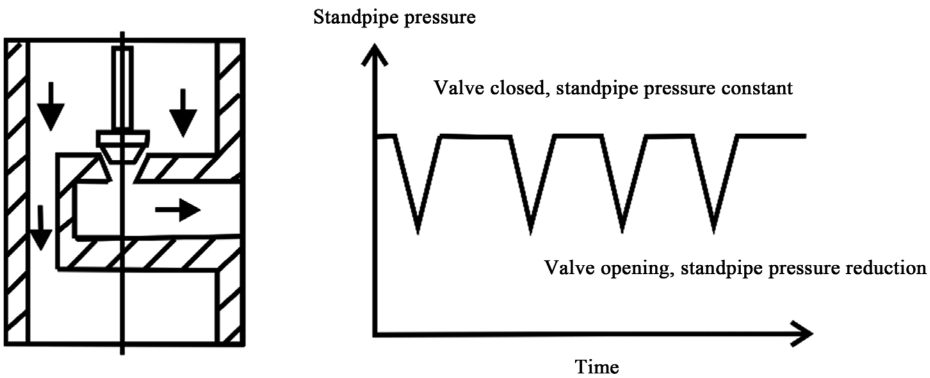

Figure 1-2. Schematic diagram of working principle of mud negative pulse standpipe pressure.

in the pressure inside the pipe, resulting in a series of pressure pulses transmitted to the ground. According to the mechanism of signal generation, it belongs to throttling signal generator (see **Figure 1-3**), and it is widely used at present.

Continuous Signal generator: it consists of a rotor and a stator, with a number of vanes on each of them. The motor will drive the stator to open or shut the opening of the stator vanes [12]. When the opening increases, the mud flows smoothly and the pressure decreases; when the opening closes, the mud flow is blocked, and the pressure increases. Instantaneous opening and closing of the rotor or continuous opening and closing will result in pulse or continuous pressure fluctuation signal. From the mechanism of signal generation, it is also a throttling signal generator (see **Figure 1-4**).

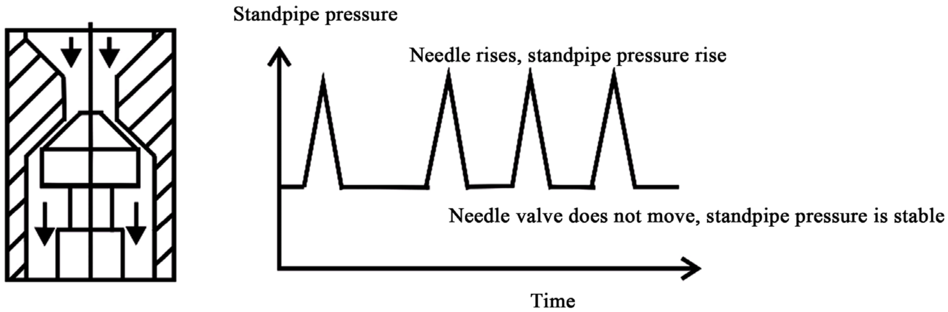

Figure 1-3. Schematic diagram of working principle of mud positive pulse standpipe pressure.

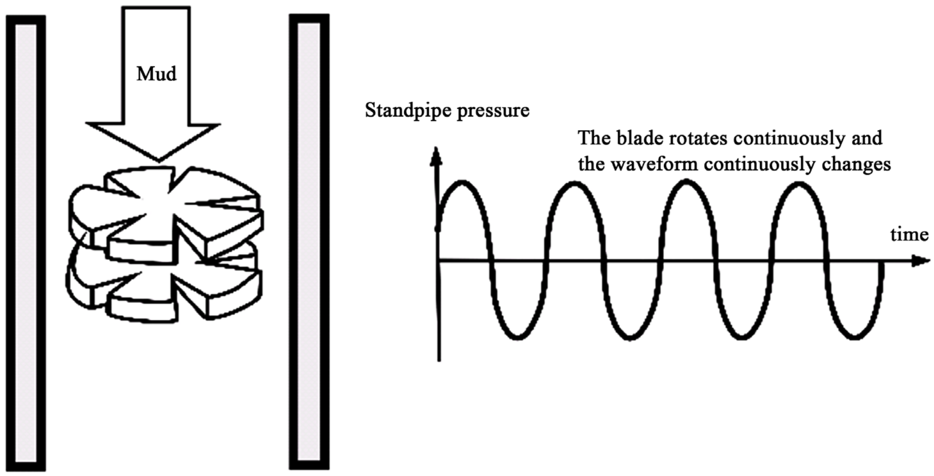

Figure 1-4. Schematic diagram of working principle of continuous wave mode.

In the mud pulse system, due to the limitation of pulse diffusion, speed regulation and other characteristics of mud system, the transmission speed of data is slow [13]. The propagation velocity of pressure wave in mud is about 1200 m/s, and the transmission signal is easily affected by noise. But the advantage is wireless and money-saving since it uses mud flow as a driving force.

Of the 3 mud pulse systems above, the transmission rate of the positive pulse and negative pulse is low, the anti-interference ability is poor, and error code is easily generated, and the continuous wave mode has high transmission rate and strong anti-interference ability. The negative pulse generator has been gradually eliminated because of its disadvantages such as pollution of annulus, low signal rate and large energy loss. At present, there are mature theoretical researches and practical applications of positive pulse MWD system both at home and abroad, such as the HDS1 (High-Speed Directional Survey) system of Halliburton company, namely the new generation of "Pathfinder" MWD system [14]; the DWD system of Sperry-Sun, and the CGMWD system developed by the project group of "The Research and Application of Geosteering Drilling Technology" in China Petroleum and Natural Gas Group Corporation. The transmission rate of the positive pulse MWD system is still low with a rate of 0.5 to 5 bit/s.

Baker Hughes has developed a new mud pulse transmission simulation tool, which is currently in the testing stage. The simulation tool simulates the expected real-time image and data quality based on the parameters set up by adjacent well data or simulated storage data. And it uses a flexible compression algorithm to match the specific application requirements, allowing the user to plan the imaging logging reasonably and complete the real-time imaging data transmission to the maximum extent. It can effectively improve transmission rate, real-time monitor drilling performance, enhance geo-steering, and achieve the optimization of remote transmission.

During the data transmission in deep well and ultra deep well, the signal attenuation will occur when the mud pulse signal is transmitted to the surface, which reduces the data quality. To deal with this problem, the Schlumberger has developed Digi Scope, a new generation of MWD data transmission platform, which operates at a frequency of 0.25 to 24 Hz, providing the maximum data transmission rate of 36 bit/s, 6 times higher than the conventional one. It uses a new modulation algorithm, and combines Digi Scope technology with the new data compression platform Orion II, improving the data transmission rate to 140 bit/s. In addition, the use of processed micronized barite drilling fluid can increase the signal strength by one order of magnitude. The specific performance parameters of the DigiScope data transmission platform are shown in **Table 1-1**.

1.2.2. Electromagnetic Transmission

Electromagnetic measurement while drilling (EM-MWD) is a new technology that has been widely applied since 1980s. There are two ways to transmit the signal [16]-[22]: using the stratum as the transmission medium and using the drill string as the transmission conductor. The downhole instrument loads the measured data onto the carrier signals, which are transmitted by electromagnetic wave transmitter [23]-[28]. The ground geophone unloads, decodes and calculates the signals in the electromagnetic wave, and obtains the actual measured data.

As an alternative to transfer the MWD data from the downhole to the ground, the electromagnetic transmission has been commercialized and applied in the middle of the 1980s, and is still in development. This method is a bidirectional transmission. It can transmit downwards and upwards in the well without mud circulation. The advantage of EM transmission is that it does not require mechanical receiving devices, and the transmission speed (1 - 12 bit/s) is fast [29] [30]. It is suitable for the transmission of directional and geological data parameters in the construction in ordinary

Table 1-1. The parameter performance of DigiScope data transmission platform.

Type	Parameter
Working frequency (Hz)	0.25 - 24
Physical transmission frequency (bit/s)	0.25 - 36
Max transmission frequency (bit/s)	>140
Power supply mode	Bipolar turbine
Memory capacity (MB)	96
Instrument outside diameter (in (mm))	4.75 (120.65)
Instrument length (ft (mm))	28.9 (8.8)
Quality (lbm (kg))	880 (400)
Applicable hole size(in)	$5^3/4$ - $6^3/4$
Working temperature (˚F (˚C))	300 (150)
Bearing pressure (psi (MPa))	25,000 - 30,000 (172 - 207)

mud, foam mud, air drilling, and laser drilling. The disadvantage is the fast attenuation of the signal, so it is suitable only for the operation in the shallow wells [31]. And the low frequency of the electromagnetic wave is close to the earth frequency, which is easily affected by the electrical equipment in the well field as well as the resistivity of the formation, so the detection and reception of the signal is relatively difficult [32].

Russia has taken the lead in the field of EM technology. Its ZTS -MWD [33] represents the advanced level of electromagnetic wave transmission. This system is mainly composed of ground equipment and downhole equipment. The downhole equipment mainly includes downhole measuring instruments and electromagnetic transmitting equipment. The underground measuring instrument consists of the azimuth sensor, the angle of the well, the sensor and the high side position sensor. The electromagnetic transmitting equipment mainly includes the signal processor, the power supply and the signal transmitter. The downhole measuring instrument is divided into two parts by insulation short connection of high strength, one is the drill string, and the other is the formation and the receiving antenna 30 - 50 meters away from the drilling rig. The ground equipment mainly includes signal receiving device, signal processor, computer and printer.

Data measured by downhole instruments are processed by signal processor and then transmitted upward along drill string and the formation. The signal received in the ground receiver is the potential difference between the two parts, and the signal is processed by the related processor and converted to a digital signal displayed on the computer. The system can not only measure data such as azimuth deviation, but also record load, vibration parameters and geophysical information on drill bits. The power of the downhole instrument comes from the turbine generator underground, whose housing is fixed with a magnet as the rotor, and the stator is axial static. When the turbine drive housing rotates, an alternating magnetic field is formed to generate electricity. The main technical parameters are shown in **Table 1-2**.

The system has the following advantages: high speed and large amount of information transmission; data transmission is not affected by the fluctuation of pump pressure; it can be used in foam drilling fluid and inflatable drilling fluid; the demanding for the sand content of drilling fluid is low; the measurable parameters are more than that of the conventional MWD; the two-way communication can be realized; the downhole instrument is only 3 meters long, and the structure is simple, which is convenient to install and use.

Table 1-2. Main technical parameters of ZTS-MWD.

Parameters	Measuring range	Error
Hole drift angle (˚)	0 - 130	±0.1
Azimuth (˚)	0 - 360	±1
Tool face angle (˚)	0 - 360	±1
Formation Resistivity (Ω·m)	0 - 200	
Maximum temperature (˚)	0 - 125	
Maximum hydrostatic pressure (MPa)	50	
Pumpage (1/s)	7 - 70	
Sand content of DF (%)	<3	
Generator life (h)	>400	
System outside diameter (mm)	108,172,195	
System length (m)	3	
Length of nonmagnetic drill collar (m)	4	
Canning material	Non-magnetic steel	

Despite the advantages, this system has the following deficiencies for domestic drilling: The turbine generator needs too much displacement and its structure is not suitable for domestic turntable whose rotating speed is very high. The connection thread is different from the domestic standard. In the performance test of ZTS-172M in Xin 110-X8 well in Shengli Oilfield in China, it is found that the system works well before the well depth reached 1600 meters, with high reliability and fast transmission rate. But at the depth of 2250 meters, the signal was abnormal because the displacement of mud pump failed to reach the rated displacement of the turbine generator.

Several new EM transmission systems have been introduced in the European and American countries in recent years: the EM-MWD system of ComputaLog Precision Drilling; the E pulse electromagnetic transmission system of Schlumberger Corp (the maximum transmission rate is 12 bit/s); the electromagnetic MWD system of the Halliburton Sperry-Sun; and the Trend SET MWD system of Weatherford.

Recently, in order to solve the problem of signal attenuation of electromagnetic telemetry system at deepened depth, Weatherford launched a new electromagnetic teletransmission antenna system named EM Casing Link (**Figure 1-5**) [34]. The instrument is composed mainly of a 0.5 inches insulated coaxial cable. The signal receiver is located in the hole and the signal passes through the insulated cable outside the casing pipe string to the ground transceiver, which reduces the adverse effect of the high barrier layer on the signal transmission, thus ensuring the intensity of the electromagnetic signal and enlarges the range of the operation depth by increasing the signal-to-noise ratio.

In a horizontal well in Texas, the U.S. Corlena petroleum, the operator, applied the EM Casing Link to the depth suitable for electromagnetic remote transmission, and used the electromagnetic pulse system to measure and transmit MWD data without affecting the pumping operation. The final data transmission rate was up to 100%, which was higher than the mud pulse transmission. It also shortened the drilling time and saved the operating costs.

BlackStar II, an electromagnetic telemetry MWD instrument, has been introduced recently by the NOV Wellbore Technologies. It is a member of InTerra sensors family.

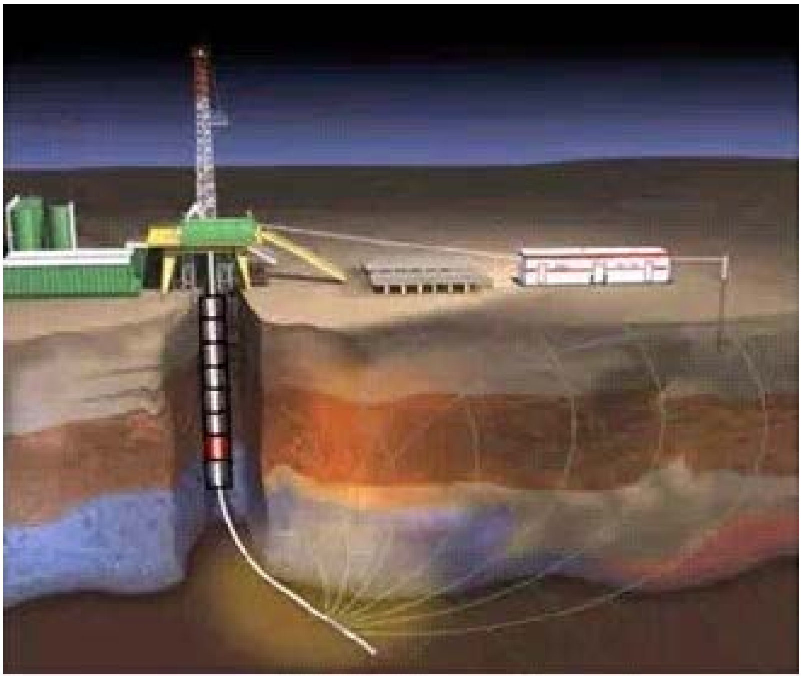

Figure 1-5. The new electromagnetic remote transmitting antenna system EM Casing Link of Weatherford.

The instrument uses electromagnetic telemetry to transmit data, and simultaneously carries out the connection operation, which improves the measurement speed and accuracy. The EM system uses low frequency electromagnetic waves to transmit information through the earth's crust. The information is received by the ground antenna, compiled and processed by the computer, and displayed on the monitor. The information is not affected by mud or cable transmission.

The EM instruments do not carry moving parts, so it can be applied to air drilling or in environment of high leakage of circulation materials, in which the mud pulse instrument is not applicable. The BlackStar II electromagnetic telemetry instrument transfers the measured data to the ground to facilitate the control and monitor of the position and orientation of the drill bit. The instrument can transmit data during the connection with the ground, greatly reducing the non-productive time compared with the conventional mud pulse instruments. The new EM system is so flexible that it has been widely used of MWD, such as underbalanced drilling, under pressure formation, vertical control drilling and coalbed gas formation.

Since the end of twentieth Century, the China Institute of Petroleum Exploration and Development has carried out a thorough and systematic study of the short transmission technology of the underground electromagnetic signal, and has successfully developed the NBLOG-1 measurement section, which is used for measuring the slope angle, the resistivity and the natural gamma near the bit. Zhao Yongping of Harbin Institute of Technology has also studied the signal transmission of electromagnetic wave, and established the model of the electromagnetic channel of the oil well, and established an experimental system to test the signal transmission capacity.

SEMWD-2000B [35] (**Figure 1-6**), developed by No. 22 Research Institute of China Electronics Technology Group Corporation, is an electromagnetic wave MWD system applicable to the development of oil and gas field and coal bed gas. The downhole tools has a Salvageable lower key; the small hole shrinkage stabilizer; the integrated design of short joints centralizing, shock absorption and the skeleton; a single section measurement device integrated by azimuth gamma and the annular pressure. The ground tools has automatic closed-loop gain control, standard WITS input and output interface, making the product simple to operate.

1.2.3. Sound Wave Transmission

The sound wave transmission mode is to transmit signals by means of sound waves or

Figure 1-6. SEMWD-2000B electromagnetic MWD.

seismic waves passing through the drill pipes or the formation [36]. First put the measuring instrument and sound wave radio transmission system down into the hole with the drill pipe or the oil pump. The measuring instrument transforms various underground parameters into the digital information, and then encodes and stores the information. The instrument transmits the binary code pulses representing the underground parameters to the control circuit, which sends the acoustic wave vibration signals. The signals are transmitted along the drill string or the tubing to the ground, received by the sound wave receiving probe installed at the wellhead, and then sent into the storage media after amplification [37] [38]. The data are processed and interpreted to obtain the current formation evaluation or production dynamic data of the well.

Acoustic telemetry can improve the data transmission rate significantly and increase the wireless transmission rate by 1 order of magnitude, reaching 100 bit/s [39].

Like acoustic telemetry and electromagnetic wave telemetry, sound wave telemetry needs no mud circulation, thus easy to operate and the investment being little. The drawback is that the attenuation is very fast and is easily interfered by the environment. The low intensity signal generated by the borehole and the acoustic noise generated by the drilling equipment make it difficult to detect the signals [40]. To solve this problem of fast attenuation in the drill string, a relay station must be installed in the drill string every 400 - 500 meters, which consists of a receiver, an amplifier, a transmitter, and a power supply [41]. To make the drill string work normally in deep depth with so many elements added, the acoustic information channel of MWD system must be very complex, so the maximum depth of the well is 3000 - 4000 meters [42]. Santia National Laboratory of the US developed acoustic telemetry technology, which quickly transmits information by the stress wave of the drilling pipe instead of the pressure pulse of drilling fluid.

After many field tests, a new type of acoustic transmission system XACT AT has been formally put into commercial applications. It is suitable for a variety of drilling environment, which is capable of rapid operation decision-making, reducing drilling risks and improving the drilling efficiency. The XACT AT system consists of an acoustic transmitter, a transceiver, a processing control module and a sensor module. By using a number of repeater with holes and hoops, an efficient data transmission of 30 bit/s can be realized at any depth. In order to optimize the signal strength and transmission speed, the system can also adjust the repeater spacing according to the well deviation, which is usually 5000 - 6000 ft in small angle wells and 2000 - 3000 ft in high angle and horizontal well. The data is usually transmitted to the ground in about 10 to 40 section, influenced by the depth of the well, the measuring section and the number of instruments. A small accelerometer is used to decode the acoustic data on the ground and then transfer the data to the well field.

1.2.4. Mixed Measurement

The mixed measuring system is a wireless MWD system with two transmission modes, electromagnetic wave and mud pressure pulse. In practice, an electromagnetic wave transmitter, a pulse generator and a probe tube are organically combined through reasonable electrical and structural design. The two transmission modes can be combined or to function on their own. This system is very efficient as it is compatible with two transmission modes, and the ground system can process and decode two kinds of signals at the same time. The system can switch between the two modes by a remote control on the ground.

The mixed measuring system can improve the reliability of the instrument and reduce the rate of instrument failure. The limitation of the short transmission depth of the electromagnetic wave can be compensated for through the pulse instruments. And the advantage of the electromagnetic wave, such as fast transmission rate, short time inclination survey, and applicability to the leakage of well, is made the best use of so as to increase speed and efficiency.

The mixed measuring system of SMMWD-3000 [43] (**Figure 1-7**) is a new type of wireless measuring equipment used in the directional service of drilling engineering. The underground equipment and ground equipment transmit data through the electromagnetic wave or mud pressure wave. The two transmission modes can work simultaneously or separately to ensure the success rate of the measurement.

The main technical indicators of the system are:

1) The highest temperature: 150˚C;

2) Maximum environmental pressure: 124 Mpa;

3) Anti-vibration 20 g RMS 30 - 300 Hz (random); 30 g 50 - 300 Hz (sine); Impact resistance 1000 g/0.5 ms.

4) Continuous working time of the system: more than 200 hours;

5) Average failure time of the system: greater than 200 h;

6) Measurement accuracy, hole deviation: 0˚ - 180˚ ± 0.1˚

Location: 0˚ - 360˚ ± 1.0˚

Tools: 0˚ - 360˚ ± 1.0˚

Figure 1-7. SMMWD-3000 hybrid MWD.

Temperature: 0˚C - 125˚C ± 0.1˚

Natural gamma: 0 - 500API ± 7%.

7) The electromagnetic wave transmission depth: more than 2000 meters (formation resistivity 2 - 1000 Ω·m.), maximum transmission depth of 4000 meters.

The SMMWD-3000 system works like this: the controlling center of the downhole instrument is the directional probe who works by mud pulse transmission. It has 4 working modes: dynamic and static detection, magnetic tool surface, gravity tool surface and static full measurement. The mechanical interface between the transmitter and the probe and pulse generator is connected by QDT. In the operation of mud pulse, the impulse generator is driven to generate impulse signals, and the directional control unit encodes the pulse signal and sends it to the ground receiving equipment. Under the working mode of the electromagnetic wave, the directional probe provides the data frame through the serial bus (RS-485/232). The data frame includes the magnetic tool surface, gravity tool surface and static measurement. The data are sent to the directional control unit, encoded, and then transmitted to the transmitter for data package, and then sent to the ground receiving equipment.

The transmitter is equipped with a pressure detection module to switch between two modes by starting and stopping the ground mud pump. The embedded detection program detects the set pump sequence, which means that mode switching is required, and the directional probe can be switched between the two modes only by periodically inquiring the status.

The ground system receiver filters, amplifies and collects signals, and then inputs them to the computer through USB port. The decoding software is installed in the computer with window operation interface, including waveform indication, data display, control indication, etc. The decoding software and engineering software coordinate and initialize data interface, and then initialize the transmitter and directional probe.

The Blackstar II, a recoverable measurement while drilling system developed by National OilWell Varc (NOV), has two data transmission modes: electromagnetic (EM) and mud-pulse (MP). This system switches between electromagnetic remote transmission and mud pulse remote transmission through EM or RPM transmission, thus reducing the cost of replacing equipment caused by re-tripping and running the drill. The system adopts different modules to configure downhole instrument strings and improves the MWD ability to the greater extent. The azimuth collected downhole, and the drilling and formation measurement data are transmitted to the surface through electromagnetic waves or pressure pulses, and are processed and displayed on the drilling control platform.

MWD sensors provided by this system include azimuth, gamma, internal pressure and annulus pressure, axial vibration and radial vibration, ROM and temperature. Through a special conversion module, the existing standard mud pulse generator can operate with Blackstar II system without modification. Blackstar II has diversified power management capabilities: the maximum output power can be increased to 40 w, the transmitter can be turned off when rotating, the module can work in 28 v groups, and dual battery support can be provided.

1.3. Performance Comparison and Prospects

To sum up, the different modes of transmission have their advantages and disadvantages and application limitations (see **Table 1-3**).

The transmission rate of wired transmission mode is high, and information can be transmitted bidirectionally. The cable mode and special drill pipe mode can also directly supply power to downhole sensors, but the manufacturing process is relatively complex, and often interferes with the normal drilling [44]. In wireless transmission mode, drilling fluid pulse method is widely used at present. Its advantage is there are no special requirements and restrictions on drilling technology, and it only uses drilling fluid as power, which has little influence on normal drilling [45]. And the

Table 1-3. The comparison of information transmission mode.

transmission mode	Transmission medium	Transmission depth (/m)	Transmission rate (b/s)	reliability	Drilling fluid medium	costs
Cable transmission	cable	>6000	1 - 2 M	good	optional	higher
	Fiber optic cable	1000	1 M	good	optional	highest
	Special pipe	6000	1 - 2 M	normal	optional	highest
Wireless transmission	Drilling fluid pulse.	>6000	1 - 12	good	necessary	medium
	electromagnetic wave	600 - 6000	1 - 12	normal	optional	higher
	Sound wave	1000 - 4000	100	normal	optional	lower

communication is reliable; the data can be transmitted over a long distance. Its disadvantage is the low rate of transmission, and drilling fluid pulse transmission cannot be used in gas and gas-liquid biphasic fluids.

Measurement while drilling technology has been commercialized for only 30 years, and its communication system has been constantly improved with the continuous development of communication and electronics. It can be expected that transmission while drilling in the future needs to be further expanded in the following aspects to make historical breakthroughs

1) For wired transmission, the key of research should be: solving the technical problem of signal transmission of drill pipe joints, developing intelligent drill string which can not only supply electricity from the ground to the underground, but also transmit data bidirectionally, so as to solve the lag of data transmission; reducing the volume of electrical connectors, increasing the wear resistance and corrosion resistance of them, and increase the surface self-cleaning and oxidation layer pressure.

2) For drilling fluid pulse transmission: the research emphasis is on continuous wave pulse generator, which can generate different frequencies for signal generator according to different mechanical drilling speed, different drilling fluid, different well depth, different drill pipe diameter, different pressure amplitude and other factors, establishing a prediction and controlling model of frequency conversion transmission of continuous pressure wave. At the same time, according to torque, drilling fluid corrosion and other factors, the mechanical mechanisms of stator, rotor and impeller, such as the number of blades, impeller shape, area and thickness, are optimized to enhance their environmental adaptability.

3) For electromagnetic signal transmission: with the continuous development of electronic components which are resistant to high temperature, high voltage and has durable power supply and huge storage chips, the stability and power supply time of downhole transmitters and repeaters need to be enhanced. On the basis of existing algorithms, through continuous improvement and innovation of algorithms, the problems of signal attenuation and recovery are studied and solved, the reliability of signal transmission is improved, and the data transmission depth is increased. In application, the forms of repeaters should be improved to increase the data transmission rate and ensure the data stability.

4) For optical fiber propagation and acoustic wave transmission: more researches

should be carried out for diversified solutions to signal transmission problems and exploration of MWD telemetry technology. For optical fiber signal transmission mode, we should further reduce the development cost, prolong the service life of optical fiber, delay the wear and tear, and solve the technical problems of uninterrupted data transmission after cracking.

5) The combination of various data transmission modes, the combination of ground remote network control software system and existing data transmission modes, and intelligent drilling matching the intelligent expert database are all important research directions and development trends in the future.

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