

Original Paper

Innovative design of a fully mechanical well deviation measurement system with experimental validation

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ABSTRACT

With the advancement of ultra-deep well drilling and dry hot rock energy development, the demand for measurement-while-drilling (MWD) systems has grown increasingly critical. The electronic MWD system is difficult to complete the measurement in the downhole environment above 200 °C. In this study, a novel fully mechanical well deviation measurement system is designed, utilizing a bias structure to sense inclination and translate it into flow-related data. The system leverages the turbine's flow sensitivity to determine the well deviation. A mathematical model for well deviation sensing and signal coding was established, and a signal pulse generator capable of reflecting well deviation changes was also built. The fluid simulation of the pulse generator was carried out by using computational fluid dynamics (CFD) simulation software. The stable output state of the pulse generator under different flow rates was calculated. The feasibility of the fully mechanical well deviation measurement system was verified through theoretical calculation and simulation analysis. An experimental system for mechanical well deviation measurement was established, and the performance of mechanical well deviation sensing and measurement was analyzed. A downhole experiment was carried out to verify the reliability of this mechanical well deviation measurement system in achieving mechanical well deviation measurement.

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1. Introduction

Well deviation measurement is an indispensable task in drilling engineering, and it is of great significance for controlling well deviation and ensuring wellbore quality (Caruzo et al., 2012; Chatterjee et al., 2014). The borehole deviations affect not only the determination of the fracture azimuth, but also the distance between the treatment and monitoring wells (Gao et al., 2022). When the monitoring or the treatment wells are assumed to be vertical, often no borehole deviation survey is done and the wells are then treated as perfectly vertical. However, during the drilling process, due to the influence of formation anisotropy, well deviation is always unavoidable, especially in high-steep and soft-hard alternating formations. In geological drilling wells, over-deviation will affect the authenticity of geological data, leading to wrong

judgments and design schemes. When the deviation is too large, the drill string is prone to fatigue damage, and at the same time, it increases the chance of getting stuck. To prevent the occurrence of well deviation, many engineering technicians and many scholars have developed corresponding active deviation correction and passive deviation correction techniques to meet the requirements of different geology and well conditions (Bulant et al., 2007; Yi et al., 2009; Fossa and Guglielmini, 2022). However, whether the well deviation control is effective and whether the current well deviation is within the scope of the operation requirements require the corresponding well deviation measurement technology to determine the measurements of the borehole inclination and azimuth, which are then used to calculate the borehole trajectory (Han et al., 2022).

Measurement-while-drilling (MWD) surveying for directional and horizontal drilling processes provides the azimuth and the inclination of the bottom hole assembly (BHA) at predetermined surveying stations. Present MWD surveying tools consist of three-axis accelerometers and three-axis magnetometers mounted inside special non-magnetic drill collars between 50 and 60 feet

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behind the drill bit (Reich et al., 2003). The technology of fibre optic gyroscopes (FOGs) has been suggested to replace the three-axis magnetometers (Noureldin et al., 2002; Xue et al., 2014).

The typical rating for downhole MWD equipment for oil and gas is between 150 and 175 °C, or even only 125 °C. There are currently few available drilling systems rated for operation at temperatures above 200 °C (Salamon et al., 2020). However, electronic components are limited by their operating conditions and are unsuitable for challenging drilling environments such as high-temperature and high-pressure wells. Furthermore, the presence of toxic and highly corrosive substances underground, such as hydrogen sulfide, also poses strict requirements for the reliability of tools.

In deep oil and gas exploration and development, when the groundwater temperature exceeds 175 °C, the materials suitable for downhole tools are different from traditional ones, and both the design principles and manufacturing processes need to be redesigned. Halliburton and Schlumberger, among other oilfield service companies, have developed MWD with a temperature resistance of 200 °C. Baker Hughes has developed a directional measuring tool. Compared with traditional electronic measuring equipment that can only withstand 175 °C, through design simplification, thermal shielding packaging and other modifications, the heat resistance of downhole electronic equipment can be gradually changed (Ma et al., 2016). However, its application cost is relatively high and it is still in the experimental stage.

Drilling of geothermal wells in enhanced geothermal systems (EGS) requires precise positioning of injection wells and production wells. Such precise positioning can only be achieved through directional drilling systems (DDS) and precise MWD systems. There is no directional drilling system in the industry that can withstand a temperature of 300 °C in a typical EGS well yet. With the continuous increase in the demand for deep and ultra-deep well exploration and development, deep and ultra-deep wells are often accompanied by high temperatures and pressures. The highest downhole temperature of the deep subsurface Tako-1 well is 220 °C and the highest pressure is 145 MPa. The existing high-temperature electronic inclinometers are difficult to work for a long time in this environment. The cost of wired transmission under high temperature and ultra-deep conditions is prohibitively high (Yan et al., 2019; Qu et al., 2024).

At present, there is no directional measurement system in the industry that can withstand the higher temperature (above 300 °C) of hot-dry-rock deep wells (Liu et al., 2022). The above-mentioned electronic high-temperature drilling measurement tools are difficult to meet the long-term downhole measurement tasks. National Oil Well Varco Inc. and other companies have developed a mechanical wellbore deviation measurement system (Chatterjee et al., 2014). This tool adopts a fully mechanical structure, overcomes the influence of temperature on electronic components, solves the problem that existing measuring instruments cannot measure the inclination angle in harsh downhole environments, and realizes wireless measurement of the inclination angle while drilling (Lunney et al., 2017). However, this structure has significant drawbacks: Firstly, the measurement range is within 17°, making it impossible to complete the large inclination measurement task similar to the HDR process. Secondly, by counting the number of positive pulse signals to determine the well deviation, it is prone to signal loss due to noise interference during long-distance transmission.

Given the limitations of existing MWD instruments under high-temperature and high-pressure conditions, this study designed a fully mechanical well deviation measurement system to address challenges such as poor temperature resistance of electronic MWD instruments. This study is organized as follows: Section 2 introduces the measurement principle and geometric characteristics

of the mechanical well deviation measurement system. Subsequently, Section 3 presents the generation principle of pressure waves and signal modulation characteristics, and establishes the corresponding theoretical and simulation models. Next, Section 4 discusses the numerical analysis results and builds an experimental system to carry out the reliability analysis of the mechanical measurement system. Finally, downhole experimental analysis is performed on the mechanical well deviation measurement system.

2. New design of fully mechanical well deviation measurement system

2.1. Overall design

The design of wireless MWD involves three aspects of technology: downhole measurement, information transmission and surface information reception. Downhole measurement is one of the key technologies of MWD. Currently commonly used wireless MWD techniques include directional parameters measurement while drilling, logging while drilling and seismic while drilling, etc. These downhole instruments use mechatronics technology, which can measure many parameters, and have a wide range of applications in the field of petroleum engineering.

As shown in Fig. 1, the main function of the well deviation measurement system in this paper is to measure the well deviation, so its downhole measuring instrument is relatively simple, and it adopts a purely mechanical structure, instead of conventional electronic measurement technology, all of the well deviation measurement, pulse signal control and generation are completed by mechanical mechanism. This not only improves the reliability of downhole instruments but also improves their ability to withstand high temperatures, making the instruments more adaptable. The working principle of the entire system is as follows: The deflection structure deflects by a certain angle under the action of the well deflection, and the well slope information is converted into flow changes through the internally designed control flow structure. Under the action of different flow rates, the turbine drives the mud pulse generator to generate mud pulse signals with amplitude-frequency variations, thereby converting the well deviation information into mud pressure pulse signals.

Information transmission technology is used to provide an effective and reliable transmission channel for information between downhole and surface to achieve information exchange and control between surface and downhole. Mud is adopted as the pulse signal transmission medium to realize long-distance signal transmission (Yang et al., 2022). The surface signal receiving system is used to receive downhole information, decode, calculate and process the received downhole information in order to obtain the required downhole data and information.

2.2. Well deviation measurement and data coding

Mechanical inclinometer in this system is its core technology. The basic principle of mechanical inclinometer is based on the principle of gravity as shown in Fig. 2. This structure can expand the measurement range of well deviation and enhance the stability of the well deviation sensing structure during the application process. The spherical pendulum structure can realize the inclination induction in the range of 90°. When the inclination is at a certain angle, it drives the connected spherical valve to open different valve ports (signal transmission area). It contains two gravity eccentric mechanisms, one axial eccentric block is used to generate a well deviation reference plane, and the second vertical eccentric block senses the well deviation and drives the spherical

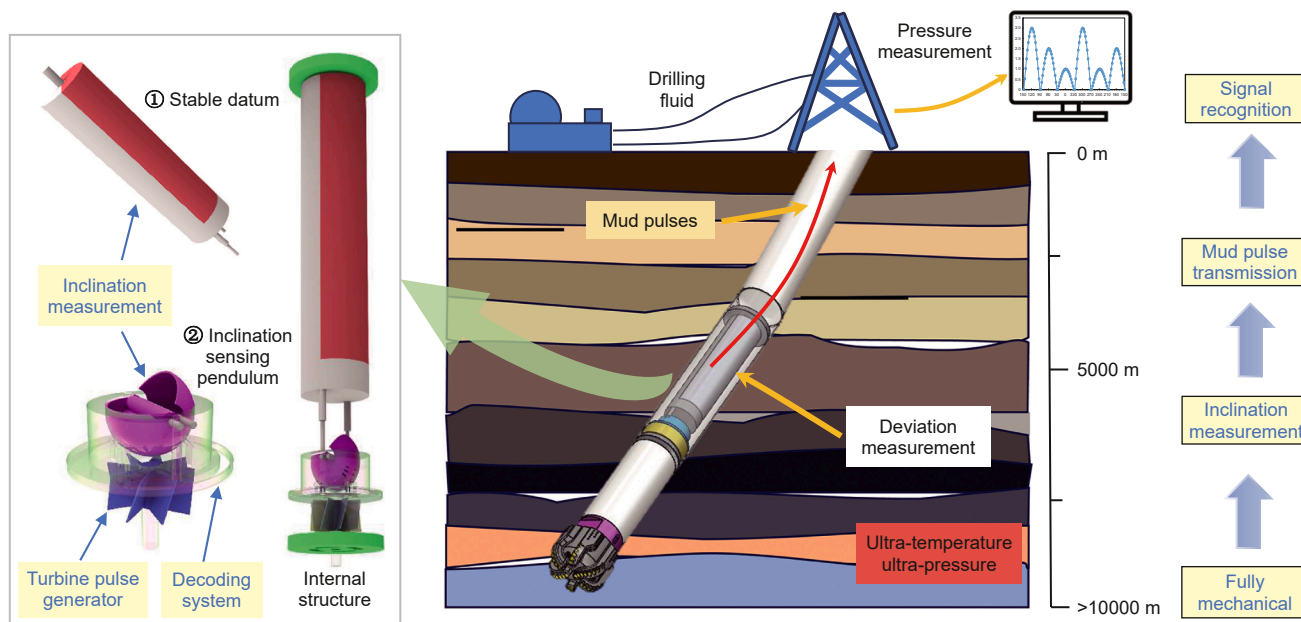


Fig. 1. Schematic diagram of the fully mechanical well deviation measurement system.

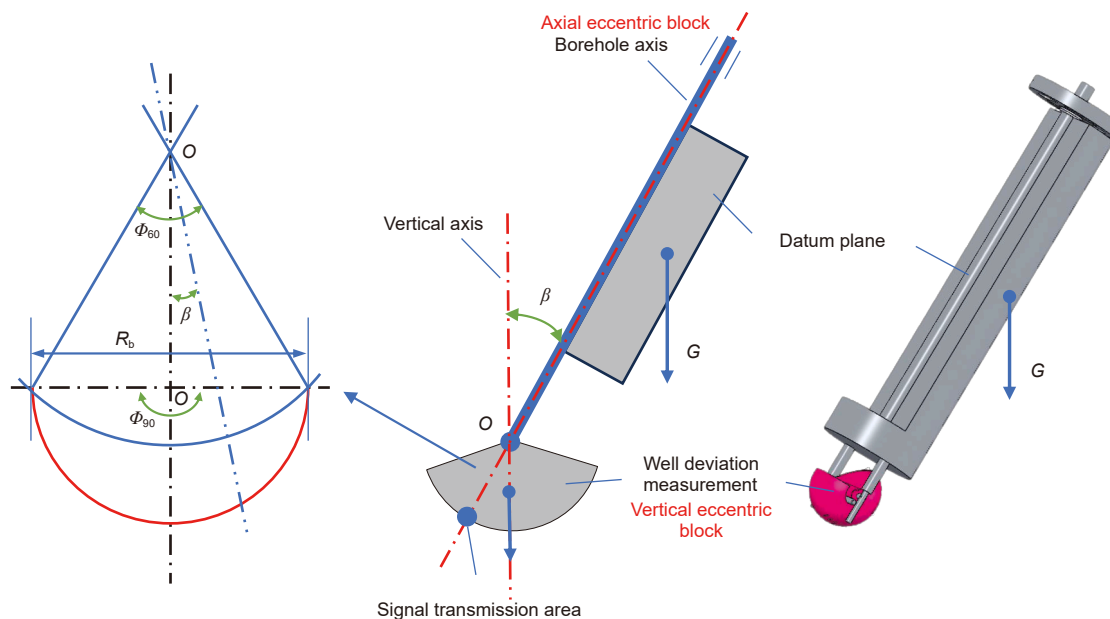


Fig. 2. Basic principle of mechanical inclinometer when the deviation is β .

encoder to rotate. When the well deviation is β , the angle of the signal transmission area of the encoder disk and the vertical axis is also β , therefore, the well deviation signal is transmitted to the surface through another mud pulse generating device. Due to the limitation of the instrument diameter R_b , the larger the measurement range, the lower the measurement accuracy. The position of the center of rotation O can be adjusted to set the measurement range, according to the different positions of the center of the circle, we can achieve two types of well deviation range 60° and 90° , representing the measurement range of well deviation is 60° and 90° respectively.

2.3. Hydraulic turbine realizes continuous pressure wave

Hydraulic turbine is the most common energy conversion device that converts hydraulic pressure into rotary motion, which are commonly used in wind energy, hydraulic turbines, hydraulic motors, etc. (Liu et al., 2019). The system utilizes a water turbine to drive the lower disc valve (Fig. 3). This is achieved through a conversion process where the hydraulic energy of the working fluid is transformed into mechanical shaft power, thereby enabling the decoding valve's rotation.

The turbine torque T_t can be expressed as follows:

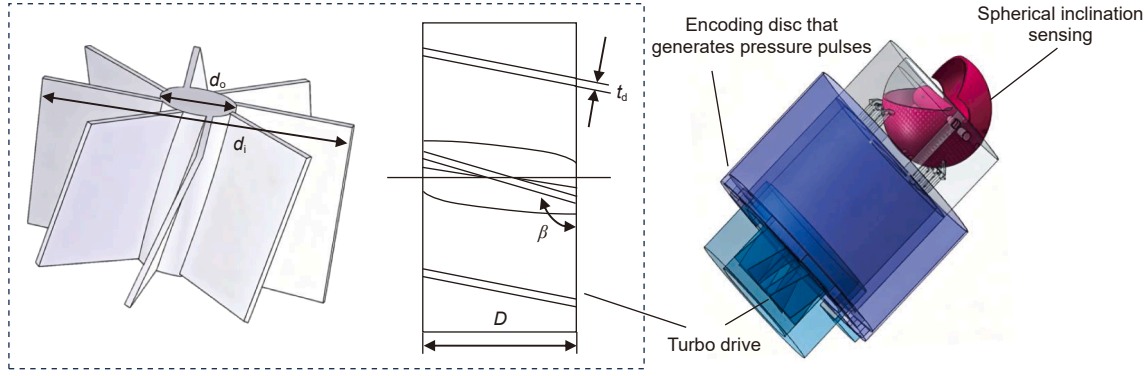


Fig. 3. Hydraulic turbine is used to drive the lower disc valve to rotate.

$$T_t = \rho Q_i \cdot R \cdot \left(\frac{C_z}{\tan \beta'} - \omega R \right) \quad (1)$$

wherein Q_i is the effective flow rate into the turbine blade flow path; ρ is the drilling fluid density; R is turbine equivalent radius, $R = (d_o + d_i)/2$, where d_o is the inner hub diameter and d_i is the outer diameter of the turbine blades (Fig. 3); C_z is turbine fluid axial velocity coefficient; β' is turbine blade angle.

$$C_z = \frac{Q_i}{\pi R (d_o - d_i) \cdot \left(1 - \frac{nh}{2\pi R \sin \beta'} \right)} \quad (2)$$

wherein n is the number of blades and h is the normal thickness of the blades.

The conversion power of the turbine blade can be expressed as:

$$W_t = T_t \omega \quad (3)$$

Working fluid flow is inevitably accompanied by energy loss during turbine blade flow and energy conversion. Energy loss is usually divided into three categories: hydraulic loss, volume loss and mechanical loss. The energy loss is not considered in this article.

A further innovation of this study lies in utilizing the turbine speed, which varies with flow rate, to modulate the pressure waveform generated by the encoder valve. By analyzing the change frequency of pressure wave, the well deviation angle can be obtained. Compared with the pressure waveform analysis, the deviation information transmitted by frequency is more accurate and not easy to be attenuated.

3. Modeling and methods

3.1. Principle of pressure wave generation

The most common and mature method for downhole communication is mud pulse, which dates back to the middle of the 19th century. During the drilling process, the pumps at the surface circulate the mud down to the drill string through the pressure pulses (Giosio et al., 2017). The mud passes through a valve that restricts and generates the pressure waves. The pressure pulse signals in MWD systems are encoded by various techniques to carry the critical information.

The generation of pressure wave signals can be expressed by the simple model shown in Fig. 4. The area of section 1-1 is A_1 , the area of the orifice section is A_0 , and the area of the jet contraction section 2-2 is A_2 . Different from the free jet, the downstream of the

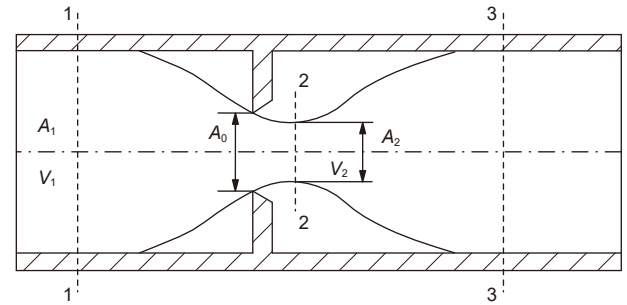


Fig. 4. Unsteady flow of orifice.

orifice is not connected with the atmosphere. So, the liquid flow will diffuse after passing through the orifice, and it is at its highest velocity at the jet section with the minimum pressure. With the diffusion of the jet flow, the velocity decreases and the pressure shows a little recovery. However, due to the resistance loss at the orifice, the pressure cannot be completely restored.

For the incompressible liquid between section 1-1 and jet section 2-2, Bernoulli's equation is listed as follows:

$$\rho \frac{\partial \phi_1}{\partial t} + \frac{\rho \alpha_1 v_1^2}{2} + \rho g z_1 + p_1 = \rho \frac{\partial \phi_2}{\partial t} + \frac{\rho \alpha_2 v_2^2}{2} + \rho g z_2 + p_2 + \zeta \frac{\rho v_2^2}{2} \quad (4)$$

In above equation, $Z_1 = Z_2$, ϕ is the velocity potential function, $\partial \phi / \partial x = v$, $\phi_1 = v_1 x_1$, $\phi_2 = v_2 x_2$ at section 1-1 and section 2-2. Also, it can be known from the continuity equation that $v_1 A_1 = v_2 A_2 = v_2 C_d A_0$, by substituting the above equation into Eq. (4), it can be drawn:

$$P_1 - P_2 = \rho \frac{\partial (v_2 x_2 - v_1 x_1)}{\partial t} + \frac{\rho v_1^2}{2} \left((\alpha_2 + \zeta) \left(\frac{A_1}{C_d A_0} \right) - \alpha_1 \right) \quad (5)$$

The upstream velocity v_1 is assumed to be constant, whereas the orifice flow area varies with time. In view of the fully turbulent flow within the jet cross-section, the kinetic energy correction factor is taken as $\alpha_2 = 1$. Usually, A_0 is much smaller than A_1 , so α_1 can be ignored, while the maximum flow area of the rotary valve of continuous wave generator, cannot be ignored when compared with the flow area of drill pipe, so α_1 should be retained in the above equation. Then:

$$\Delta P_0 = \frac{\rho Q^2}{2 C_d^2 A_0(t)^2} \left(1 + \zeta - \frac{2 C_d x_2}{Q} \frac{\partial A_0(t)}{\partial t} \right) \quad (6)$$

wherein Q is the drilling fluid flow through the valve port, m^3/s ; C_d is the flow coefficient of the valve port. When the Reynolds number (Re) is greater than the critical Reynolds number, the flow coefficient remains approximately a constant. When $Re > 10^5$, $C_d = 0.60\text{--}0.62$; When the liquid flow does not completely contract, $C_d = 0.7\text{--}0.8$ (Chen, 2017). A_0 is the flow area of the valve port, m^2 ; ρ is drilling fluid density, kg/m^3 ; ΔP_0 is the pressure difference between the valve front and the valve back, Pa.

The x_2 in the above formula increases as the flow area A_0 decreases. For the fan-shaped valve port in Fig. 3, the area S_t is closed and opened at a constant speed, assumed to be ω , determined by the driving torque of the hydro turbine as shown in Fig. 5.

When $\beta > \gamma$, the closing phases S_t can be expressed as:

$$S_t(t) = \begin{cases} \frac{1}{2}(R_s^2 - r^2)\omega t & \omega t \leq \gamma \\ \frac{1}{2}(R_s^2 - r^2)\gamma & \gamma < \omega t < \theta' \\ \frac{1}{2}(R_s^2 - r^2)(\beta + \gamma - \omega t) & \omega t > \theta' \end{cases} \quad (7)$$

wherein R_s is the outer radius of different fan-shaped valve port, while r is the inner radius of the fan-shaped valve holes. γ is the central angle corresponding to the fan-shaped valve.

When $\beta = \gamma$, the closing phases S_t can be expressed as:

$$S_t(t) = \begin{cases} \frac{1}{2}(R_s^2 - r^2)\omega t & \omega t \leq \gamma \\ \frac{1}{2}(R_s^2 - r^2)(2\gamma - \omega t) & \omega t > \gamma \end{cases} \quad (8)$$

When $\beta < \gamma$, the closing phases S_t can be expressed as:

$$S_t(t) = \begin{cases} \frac{1}{2}(R_s^2 - r^2)\omega t & t \leq \theta' \\ \frac{1}{2}(R_s^2 - r^2)\beta & \theta' < \omega t < \gamma \\ \frac{1}{2}(R_s^2 - r^2)(\beta + \gamma - \omega t) & \omega t > \gamma \end{cases} \quad (9)$$

In this paper, the flow area $A_0(t)$ can be expressed as:

$$A_0(t) = S_{H_n} - S_t \quad (10)$$

wherein S_{H_n} represents the area of a curved hole,

$$S_{H_n} = \theta'(H_n) \cdot (R_s(H_n)^2 - r^2) \quad (n = 1, 2, 3) \quad (11)$$

Take Eq. (11) into Eq. (6) to get:

$$\Delta P_0 = \frac{\rho Q^2}{2C_d^2} \frac{1}{(S_{H_n} - S_t)^2} \left(1 + \zeta + \frac{2C_d x_2}{Q} \frac{\partial S_t}{\partial t} \right) \quad (12)$$

It can be found from the above formula that the pressure difference decreases with the increase of the area change rate, that is, the signal amplitude increases as the signal frequency increases.

In engineering applications, we can simplify the calculation as shown in the following:

$$\Delta P_0 \approx \frac{\rho Q^2}{2C_d^2} \frac{1}{(A(t))^2} \quad (13)$$

Eq. (15) shows the pressure change when there is only one hole, as shown in Fig. 3, we used six drain holes and three specifications in this paper, the comprehensive area is shown in the following:

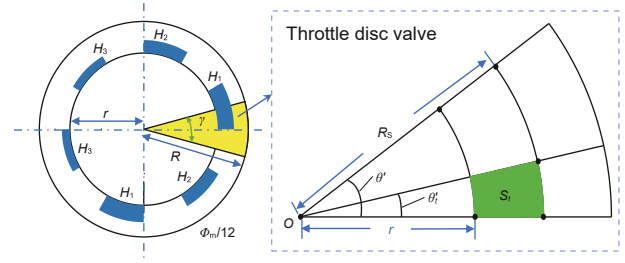


Fig. 5. Signal transmission mechanism of mechanical well deviation measurement system.

$$S_T = 2 \cdot \sum_{n=1}^{n=3} S_{H_n} \quad (15)$$

Therefore, on the encoder disc as shown in Fig. 3, the pressure changes over time function can be expressed as:

$$\Delta P_0(t) \approx \frac{\rho Q^2}{2C_d^2} \frac{1}{(S_T - S_t(t))^2} \quad (16)$$

The downhole pressure pulse waves are uploaded to the surface signal acquisition device along the drilling fluid in the drill string, and the downhole information is obtained through the collected pressure fluctuations.

3.2. Experiments and parameters

3.2.1. Accuracy analysis of well deviation measurement

In the measurement system induction well and control well, the dual bias induction system is designed. The flow of drilling fluid passed by a stable datum and an well deviation measurement pendulum separately in different wells.

(1) Low side induction of well deviation

The biasing mechanism produces sufficient deflection force G during the induction well, overcomes the system resistance, ensuring that the bias block is stable in the well. The extension of the precision of the pre-emphasis platform is mainly including the mechanical structure. When the bias torque generated by the boutique is greater than the resistance M_f at the outside connection, the bias block can induce a well-transformed change (Li et al., 2022; Chen, 2017).

In this design, as shown in Fig. 6, the rectangular coordinate system is established based on the axis and the vertical plane, and the axial and radial component forces generated by the eccentric weight block in case of well deviation are as follows:

$$F_{rt} = G_e \sin \beta \sin \phi \quad (17)$$

$$F_{rr} = G_e \sin \beta \cos \phi \quad (18)$$

In the above formula, G_e is the gravity of the bias block, N . β is well deviation, $^\circ$. Let the bias block be in the position shown in the figure below, ϕ is the angle between the center of gravity and the lower side of the wellbore, $^\circ$;

F_{rt} and F_{rr} are the tangential and radial components of X (radial eccentric force) respectively, The eccentric torque can be obtained from the above equation:

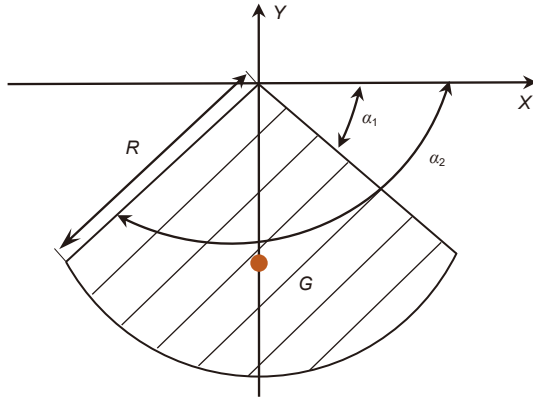


Fig. 6. Schematic diagram of the partial weight block structure.

$$T = F_{rt} \times Y_C = \frac{1}{3} \rho g l (r_2^3 - r_1^3) (\cos \alpha_1 - \cos \alpha_2) \sin \beta \sin \phi \quad (19)$$

where T is the eccentric torque produced by the eccentric weight, N·m. When $\alpha_1 = 0$ and $\alpha_2 = \pi$, the maximum value of eccentric torque $T_{\max}$ is obtained:

$$T_{\max} = \frac{2}{3} \rho g l (r_2^3 - r_1^3) \sin \beta \sin \phi \quad (20)$$

Therefore, the whole structure can ensure $T_{\max} > M_f$ in the design process. The well deviation induction can be completed accurately to keep the deviation sensing level.

(2) Deviation flow control

Changes in well inclination cause the pendulum to deflect, thereby changing the effective flow area of the overflow passage. This change regulates the drilling-fluid flow rate and consequently the rotational state of the lower turbine. The oscillating range of the pendulum is 0° – 90° , and the equivalent overcurrent area is divided into 0° – 30° , 30° – 60° , 60° – 90° three parts, as shown in Fig. 7. The sensing pendulum institutions designed three dimensions of overflows, controlling drilling fluids of different flow at different well angles. Where A' is an equivalent area, Q is the flow rate flowing into the turbine flow, and S' is the turbine flow area.6

3.2.2. Encoder disk structure parameter design

During measurement, the higher the measurement accuracy and the larger the measurement angle, the greater the amount of

well deviation information to be transmitted. The design of the well deviation information coding system based on continuous pressure pulse signals is conducive to optimizing the structural design and improving effectiveness and reliability of information transmission.

The signal coding design introduces two forms: amplitude coding and frequency coding, that is, different well deviation correspond to different signal amplitudes and frequencies. Even if individual pulses are distorted or lost due to noise interference during transmission, the signal can still be identified and decoded as long as the morphological features of the entire pulse sequence are recognized in combination with its frequency characteristics. Such a dual-insurance mechanism guarantees the anti-attenuation performance of signal transmission and the reliability of accurate decoding.

Assume that the measuring range is ϕ_m , according to the different positions of the center of the circle as shown in Fig. 5, we can achieve any types of well deviation range between 0° and 90° , by changing the area of H_n ($n = 1, 2, 3, \dots, m$). In theory, the amount of information that can be encoded can be expressed by the following permutation and combination formula:

$$M = C_k^k \cdot A_m^m \quad (21)$$

wherein k represents the number of different combinations, m represents the grading number of the ring hole area.

The achievable values of m and k are constrained by downhole spatial limitations and the requirement that pressure wave amplitude fluctuations must exceed a specific threshold for reliable surface detection. These constraints are governed by both design and signal recognition accuracy, necessitating further investigation. As shown in Table 1, a typical encoding method ($k = 2, m = 3$) realizes 12 types of signal encoding. If the well measurement range ϕ_m is 60° , then the measurement accuracy is 5° .

According to the principle of the plate hole throttle, the encoding disc is designed according to the above parameter, the

Table 1
A typical encoding method ($k = 2, m = 3$).

Inclination	Coding	Inclination	Coding
$\phi_m/12$	H ₁ H ₂ H ₃ H ₃ H ₁ H ₂	$7\phi_m/12$	H ₁ H ₂ H ₃ H ₂ H ₃ H ₁
$2\phi_m/12$	H ₂ H ₃ H ₃ H ₁ H ₂ H ₁	$2\phi_m/3$	H ₂ H ₃ H ₂ H ₃ H ₁ H ₁
$\phi_m/4$	H ₃ H ₃ H ₁ H ₂ H ₁ H ₂	$3\phi_m/4$	H ₃ H ₂ H ₃ H ₁ H ₁ H ₂
$\phi_m/3$	H ₃ H ₁ H ₂ H ₁ H ₂ H ₃	$5\phi_m/6$	H ₂ H ₃ H ₁ H ₁ H ₂ H ₃
$5\phi_m/12$	H ₁ H ₂ H ₁ H ₂ H ₃ H ₂	$11\phi_m/12$	H ₃ H ₁ H ₁ H ₂ H ₃ H ₃
$\phi_m/2$	H ₂ H ₁ H ₂ H ₃ H ₂ H ₃	ϕ_m	H ₁ H ₁ H ₃ H ₃ H ₃ H ₁

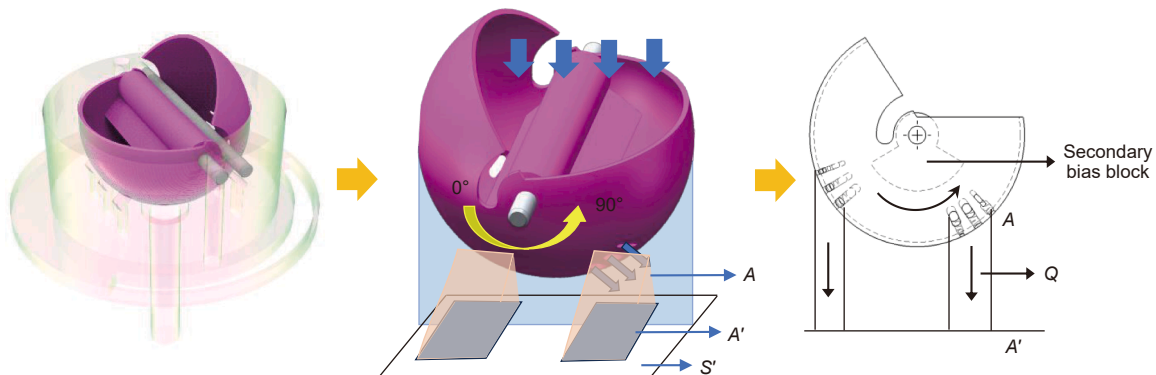


Fig. 7. Schematic diagram of the structure of overflow maturity.

encoding disk size is shown below. The center angle corresponding to a single coding hole is 30° , and the accuracy of the signal can be improved within 30° . The coding disk adopts a circular arc-shaped overflow structure, based on the small hole over-current theory, the formula can obtain a single coding hole area change in the dynamic change process:

$$A' = \frac{1}{c} \sqrt{\frac{Q^2 \rho}{2 \cdot \Delta P_i}} \quad (22)$$

wherein, A' is the over-current area of coding disk; ΔP_i is the pressure drop of drilling fluid through the disc valve. This structure is designed with the formula of the coding disk extension hole cutting area:

$$A = \frac{\omega t}{2} (R^2 - r^2) \quad (23)$$

During periodic rotation, the variation of the overcurrent area of the valve block sweeping through the coded hole is given by:

$$A = \begin{cases} \frac{\theta' \cdot \pi (R^2 - r^2)}{6 \cdot 60^\circ}, & (0^\circ \leq \theta' \leq 60^\circ) \\ \frac{(\theta' - 60^\circ) \cdot \pi (R^2 - r^2)}{6 \cdot 60^\circ}, & (60^\circ < \theta' \leq 120^\circ) \end{cases} \quad (24)$$

$$\Delta p = \frac{2\rho Q^2}{C^2 \omega^2 t^2 (R^2 - r^2)^2} \quad (25)$$

The pressure difference between the gaps at both ends of the gap should not be too large, avoiding a larger bubble air erosion, the damage of the acceleration structure, and the instability of the measurement system. Therefore, in the design process, the pressure reduction retention relationship is: $\Delta p = \frac{p_1}{p_2} < 3.5$.

The dynamic variation of the pressure and area at different coding holes can be calculated by the above formula. The three angles of the well deviation measurement pendulum mechanism can be divided into D_i ($i = 3$) in average.

3.2.3. Simulation model of pulse generator

The overall structure of the pulse generator is mainly composed of a coding disc, a turbine, and a valve block. Driven by drilling fluid, the turbine rotates the valve block. The relative motion between the valve block and coding disk adjusts the flow area and produces encoded pressure pulses. This section establishes a fluid mechanics model and verifies the feasibility of the pressure pulse coding generator through CFD simulation software.

(1) Turbo design parameters

The designed turbine drives the coded valve block for rotary motion against the coding disk. For deep and ultra-deep wells, drilling fluid supplies stable and continuous power to the turbine. The adoption of straight-blade turbine blades ensures its

advantages in terms of wear resistance and high reliability, guaranteeing the stability and sensitivity of operation. The structural parameters are shown in Table 2.

(2) Simulation model of pressure pulse generator

Fig. 8(a) is a three-dimensional simulation model of pulsed generators, and the encoding disk is located on the top of the turbine valve block. This CFD model controls the variation of the rotational speed of the turbine valve block structure by setting the area of the inlet flow channel of the turbine, the change of the flow channel area under the equivalent well deviation action, and affects the frequency variation of the signal. In the simulation model, different sizes of the turbine inlet end are set to correspond to the flow rate changes under three different well inclination angles, and the occurrence of the turbine pulse generation signal and the turbine motion state are analyzed. As shown in Fig. 8(b), a linear relationship corresponding to the well deviation and the area of the throttle hole was established. The signal characteristics of the turbine pulse generator can be analyzed by adjusting the change of the equivalent well deviation of the opening area at the turbine inlet end.

The simulation model adopts the wall function method to handle the boundary conditions of the incoming wall. The global pressure-based solver is used to carry out transient analysis calculations. The simulations are performed using the RNG $k-\epsilon$ turbulence model and second-order windward finite element format.

The turbine rotation equation:

$$J_y \frac{d^2 \theta}{dt^2} = \sum M_y \quad (26)$$

J_y is heavy rotational inertia; $\sum M_y$ is a total external atrial moment of turbine, including external load and fluid action. The torque generated by the external load and fluid action. According to the start of the water strike, the turbine changes under different flow rates. When the turbine angular velocity is stable, the turbine reaches a steady state at a certain flow rate, at which point the pressure pulse encoded signal generated by the simulation system can be analyzed.

Three pressure monitoring points are arranged in the model, including Point 1 (inlet), Point 2 (middle chamber), and Point 3 (outlet), to analyze the variation of coded pressure waves. Meanwhile, the assembly interaction of components is considered for each model combination. The volume loss caused by radial leakage is not considered during the simulation (Xu et al., 2017; Qu et al., 2024). Based on the CFD software, the solving of the flow field is completed, and the complex model grid is divided into a number of regular shapes, and the flow control equation is solved in the unit. In the model, a four-sided mesh is used to better accommodate the fluid domain and the rotation domain, and consider the boundary layer, the grid results are shown in Fig. 8(c). The data in Table 3 are the relevant parameters during the simulation process.

In non-steady-state numerical analysis, the calculation results should be independent of the grid scale and time intervals. To verify this characteristic and analyze its influence on the simulation results, this study set different mesh sizes and time steps for the same component. The detailed parameters are shown in Table 4.

(1) Time step influence analysis

The large vortex simulation results of a grid with 1.77 million grids at three different time steps of 0.05, 0.005, and 0.0005 s are shown in Table 5.

Table 2

Key parameters of the turbine and coding structure.

Main parameters	Value	Main parameters	Value
Number of blades	8	D , mm	40
Thickness, mm	1	β'	30°
Blade pitch, mm	7.85	ϕ	0.9
d_0 , mm	81	d_i , mm	20

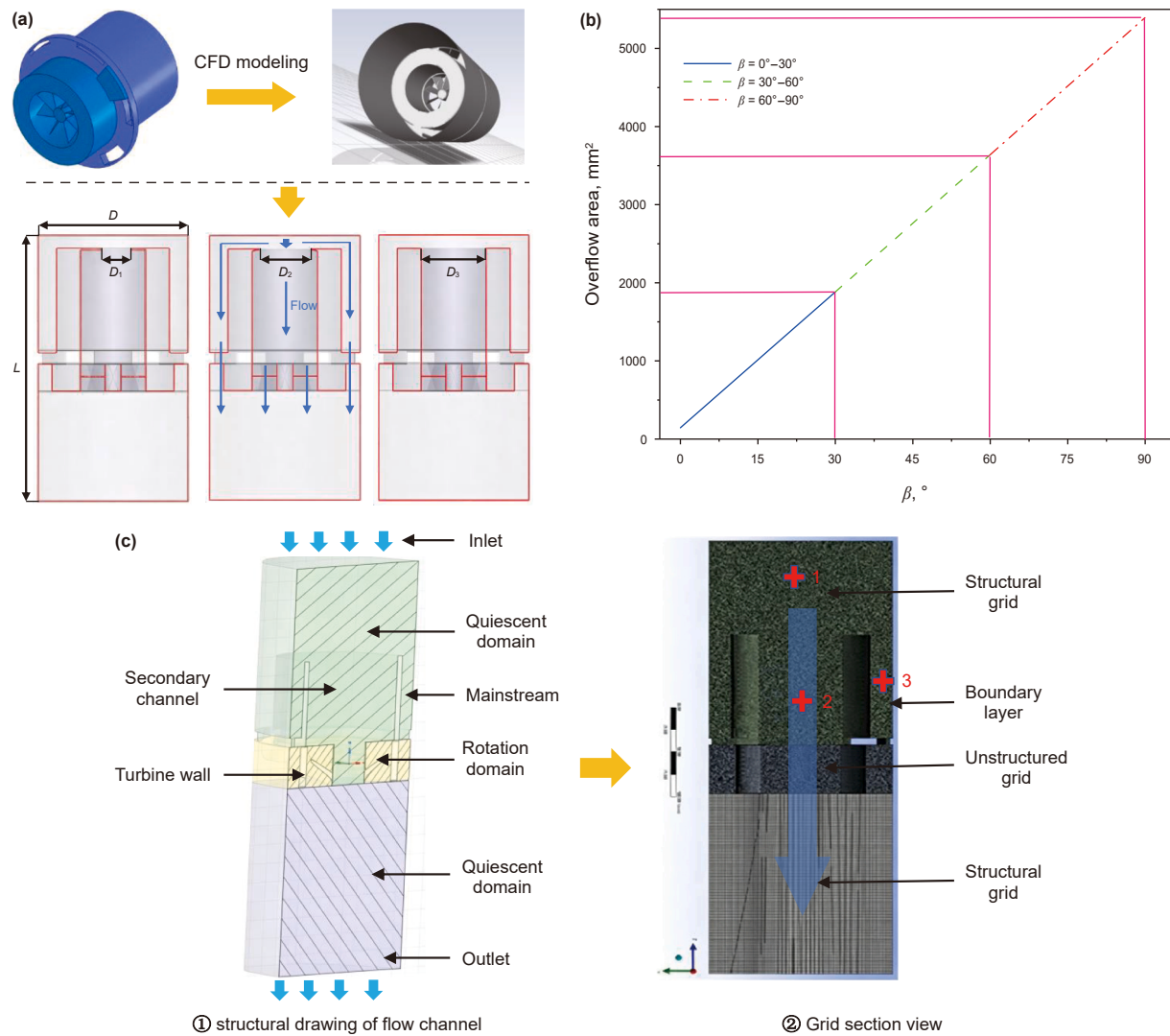


Fig. 8. Simulation model and system parameter design. (a) Pulse generator model structure diagram; (b) The relationship between different well inclination angles and flow area; (c) Pulse generator fluid domain grid division and related parameters.

Table 3

Simulation parameter.

Main parameters	Value	Main parameters	Value
Flow 1	15 L/s	D	185 mm
Flow 2	20 L/s	D_1 ($0^\circ \sim 30^\circ$)	46 mm
Flow 3	25 L/s	D_2 ($31^\circ \sim 60^\circ$)	66 mm
Flow 4	30 L/s	D_3 ($61^\circ \sim 90^\circ$)	81 mm
L	420 mm	Drilling fluid properties	Water

Table 4

Mesh sizes and time steps for grid independence verification.

Number of grids	Time step, s
9.6×10^5	0.05
1.77×10^6	0.005
2.81×10^6	0.0005

Table 5

Simulation results at different time steps.

Time step, s	Inlet pressure, MPa	Outlet pressure, MPa	Rotational speed, rpm
0.05	3.85	0.22	169
0.005	3.41	0.408	186
0.0005	3.48	0.403	189

Table 6

Simulation results of different grid numbers.

Number of grids	Inlet pressure, MPa	Outlet pressure, MPa	Rotational speed, rpm
9.2×10^5	3.95	0.35	154
1.77×10^6	3.74	0.401	179
2.56×10^6	3.69	0.42	181

By comparing and analyzing the transient simulation results with three time steps of 0.05, 0.005 and 0.0005 s, it is found that when the 0.0005 s time interval is adopted, the residual calculation can converge rapidly, and a stable solution can be obtained at

each time step. When larger time steps of 0.05 and 0.005 s are adopted, the residual curve shows obvious oscillation characteristics, although it can eventually stabilize. As shown in Table 5,

Table 7
Turbine size parameters.

Main parameters	Value, mm	Main parameters	Value, mm
D	185	D_i	0–81
d	180	d_1	170
d_2	160	d_3	150

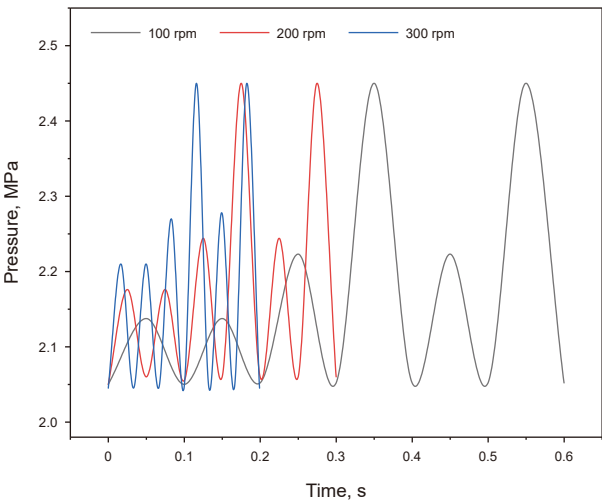


Fig. 9. Dynamic area change curve of single throttle under different speeds.

there are significant differences in the inlet and outlet pressure amplitudes obtained under different time step settings. This indicates that the selection of the time step directly affects the simulation accuracy of the self-excited oscillation characteristics in the cavity, and thus has an important impact on the calculation accuracy of the impact force amplitude. Therefore, to ensure the calculation accuracy, this study determines that the optimal time step size is 0.0005 s.

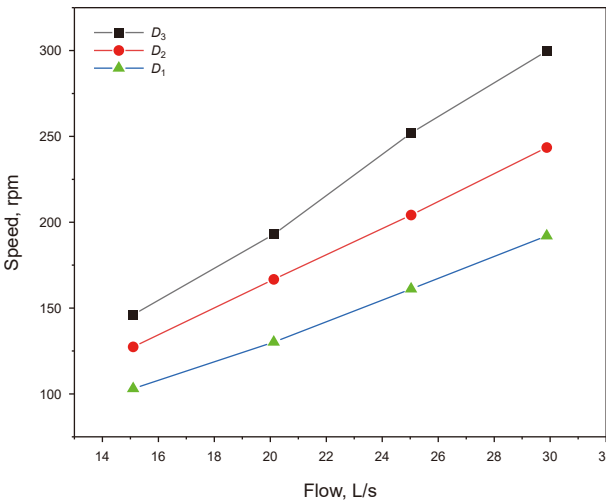


Fig. 11. Turbine speed curves at different flow rates.

(2) Analysis of the impact of grid quantity

Under the premise that the time step is fixed at 0.0005 s, large eddy simulation studies are carried out for three grid quantity schemes of 9.2×10^5 , 1.77×10^6 and 2.56×10^6 . The calculation results are shown in Table 6. All three meshing schemes exhibit good convergence characteristics. It is worth noting that when the number of grids increases to 1.77×10^6 and 2.56×10^6 , the obtained pressure pulsation characteristic parameters and turbine speed stability are very close, but there is a significant deviation compared with the calculation results of 9.2×10^5 grids. This comparative analysis indicates that reliable numerical simulation results can be obtained by using 1.77×10^6 grids for simulation calculation, and further increasing the number of grids has a limited effect on improving the calculation accuracy.

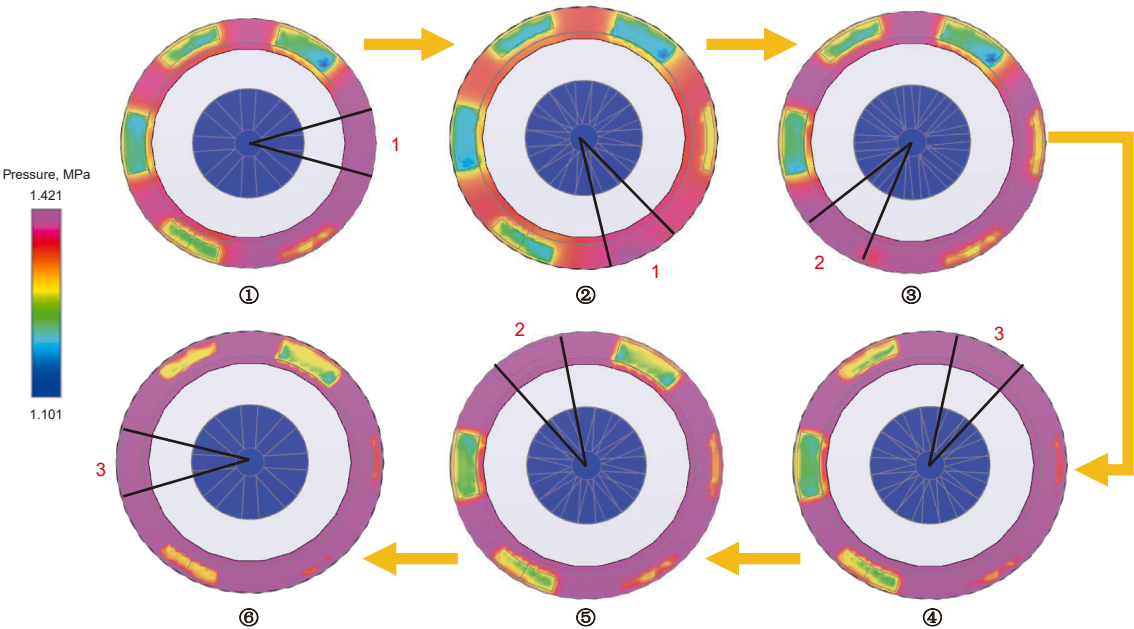


Fig. 10. Upper outlet pressure cloud, $Q = 30 \text{ L/s}$, $D_2 = 66 \text{ mm}$.

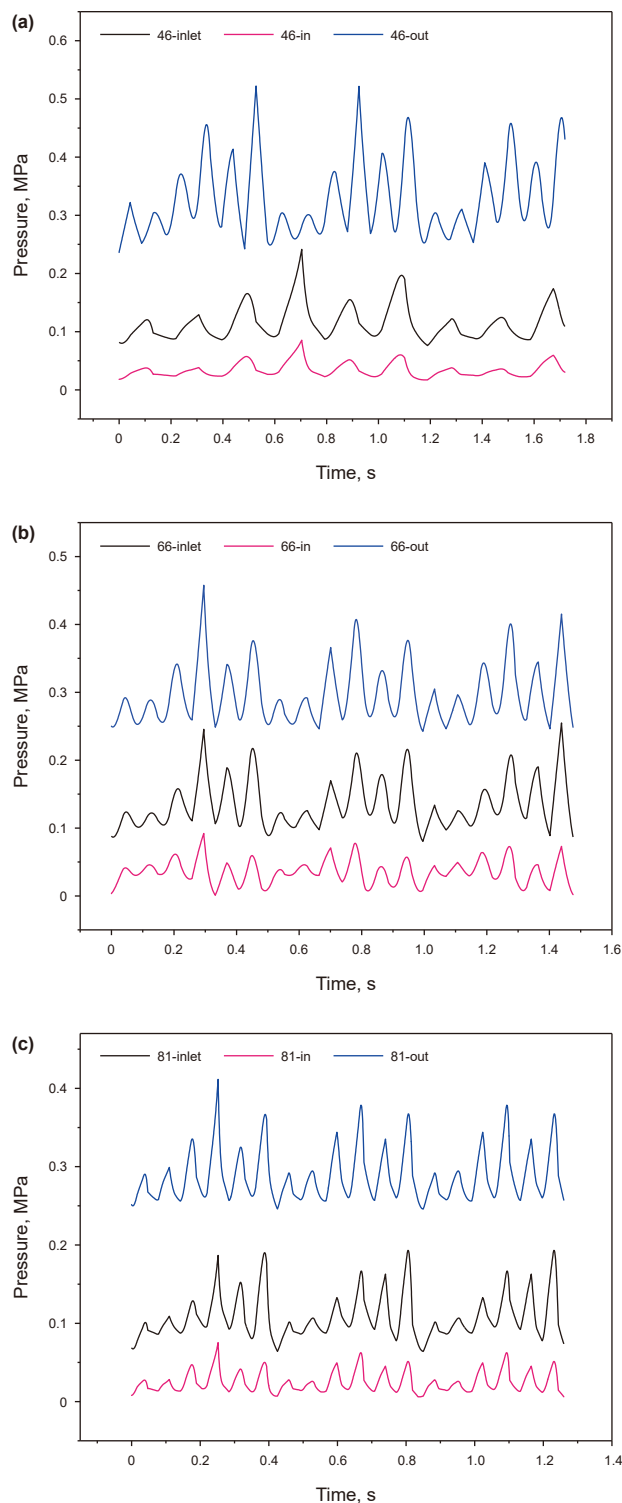


Fig. 12. Pressure pulse signals at a flow rate of 15 L/s for different diameters. (a) Structural diameter $D_1 = 46$ mm; (b) Structural diameter $D_2 = 66$ mm; (c) Structural diameter $D_3 = 81$ mm.

4. Results and discussion

4.1. Code signal theory analysis

This structure adopts a 60° interval as a single cycle for flow area variation. A full rotation of the coding disc undergoes six

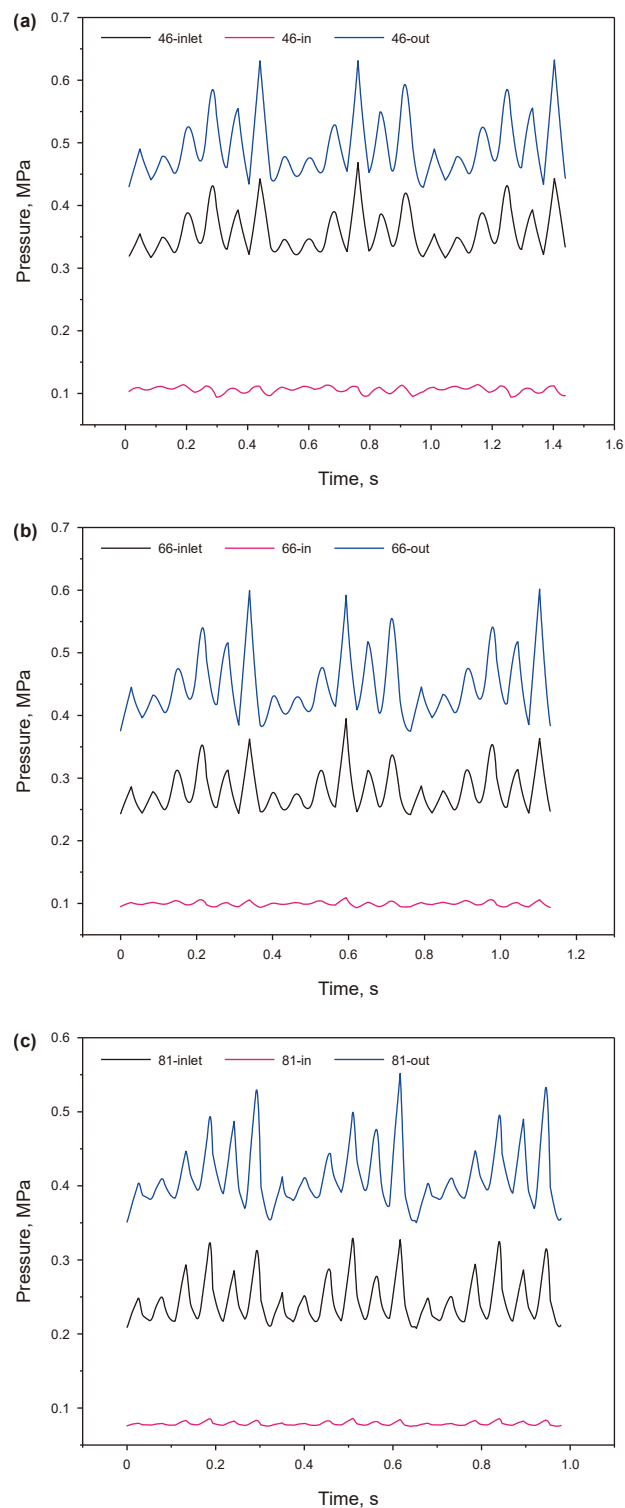


Fig. 13. Pressure pulse signals at a flow rate of 20 L/s for different diameters. (a) Structural diameter $D_1 = 46$ mm; (b) Structural diameter $D_2 = 66$ mm; (c) Structural diameter $D_3 = 81$ mm.

sequential dynamic changes in the throttling area. Using the calculation formula presented above, the dynamic throttling area variations under different rotational speeds and the dimensional parameters of the coding disc are listed in Table 7. Design parameters: The designed pressure drop of the coding disc is 3 MPa; the rotational speeds of the coding disc are set to 100, 200, and

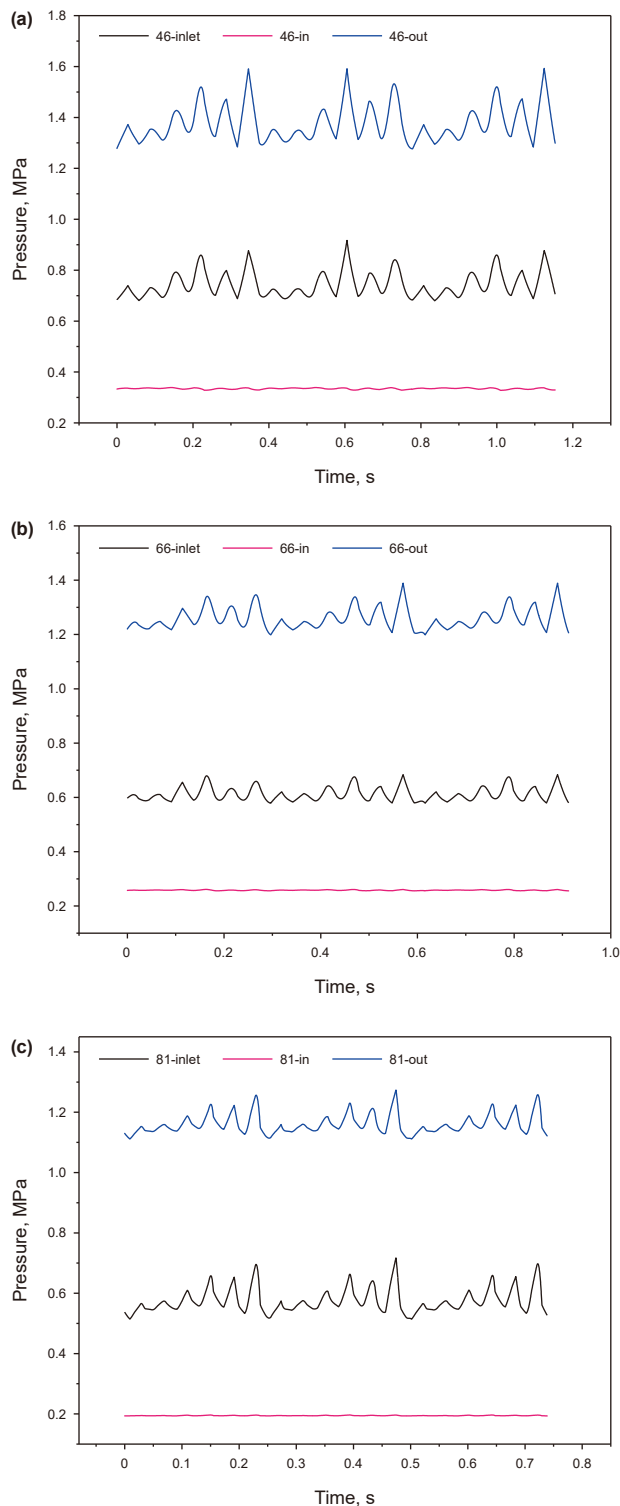


Fig. 14. Pressure pulse signals at a flow rate of 25 L/s for different diameters. (a) Structural diameter $D_1 = 46$ mm; (b) Structural diameter $D_2 = 66$ mm; (c) Structural diameter $D_3 = 81$ mm.

300 rpm; the drilling fluid density is 1000 kg/m^3 ; the flow coefficient of the drilling fluid is $C = 0.75$; and the inlet flow rate of the system is 30 L/s.

Combined with the design method of the signal in Section 3, the pressure fluctuation characteristics obtained by the coding

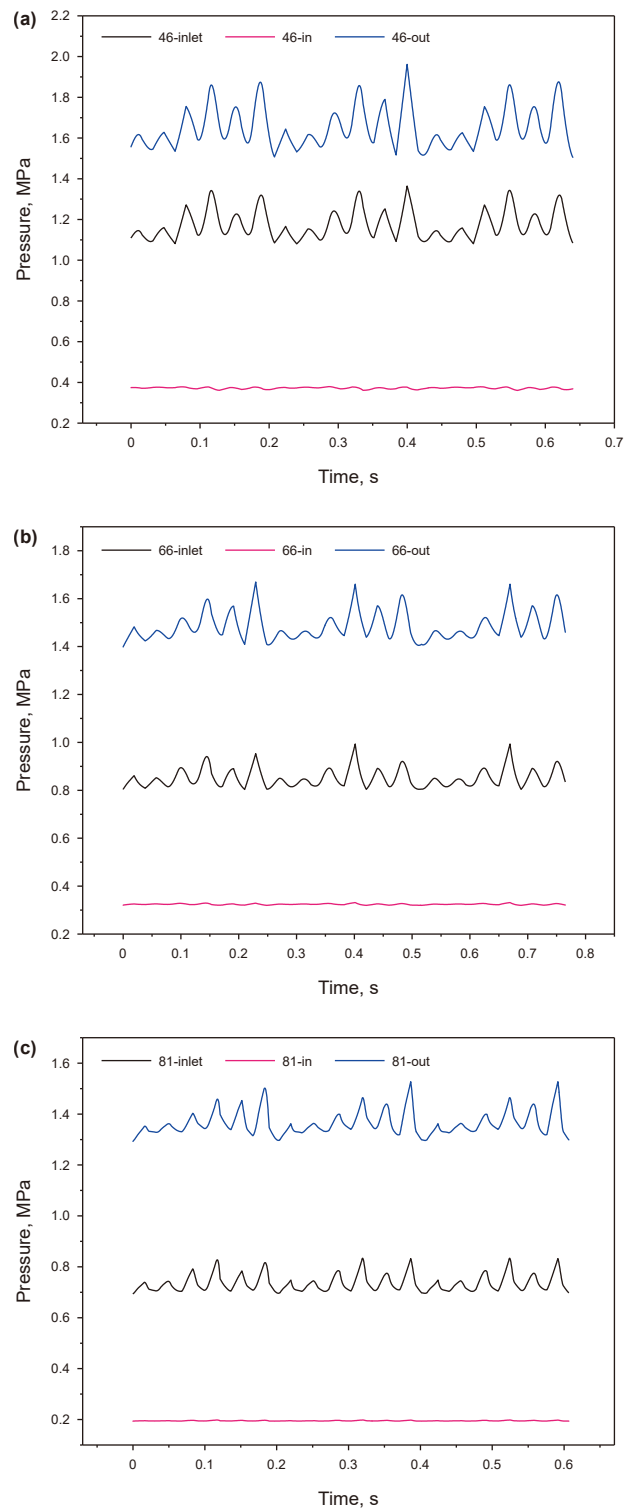


Fig. 15. Pressure pulse signals at a flow rate of 30 L/s for different diameters. (a) Structural diameter $D_1 = 46$ mm; (b) Structural diameter $D_2 = 66$ mm; (c) Structural diameter $D_3 = 81$ mm.

disk within one rotation period in Fig. 9 can be obtained. Its dynamic change is approximately a cosine curve. The lower the rotational speed, the greater the duty cycle. The amplitude variation of the waveform in the curve verified the feasibility of the theoretical design model.

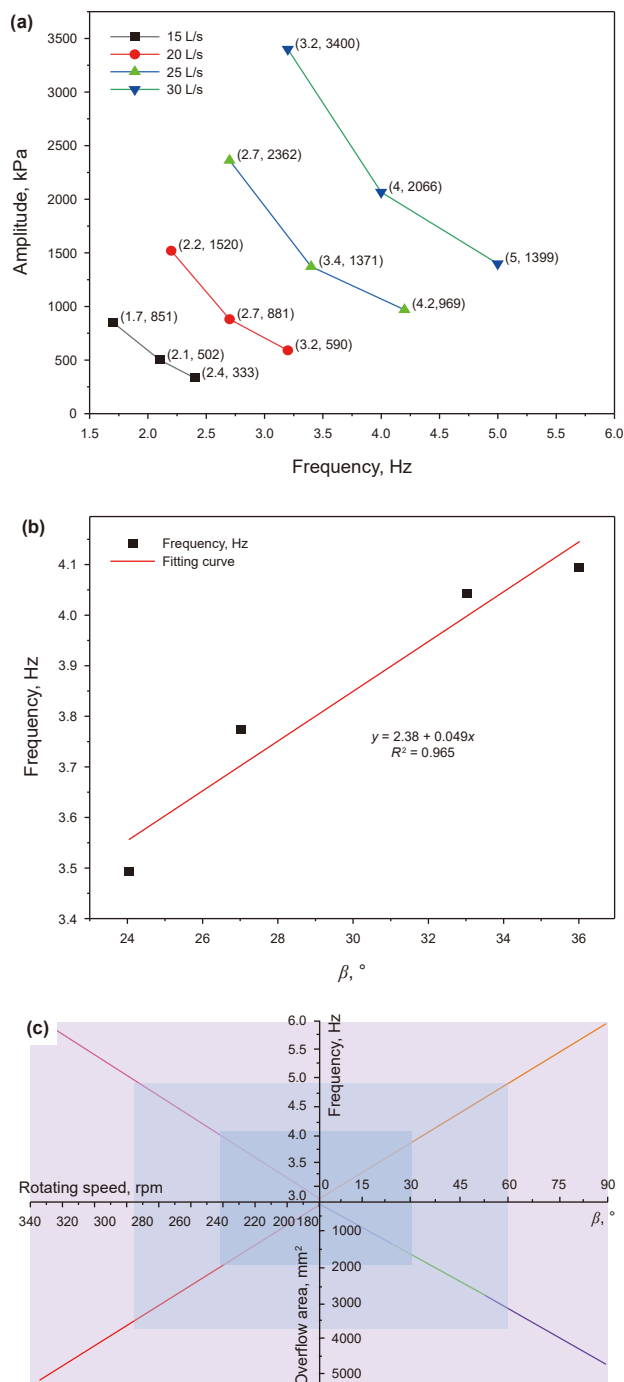


Fig. 16. Simulation signal characteristics. (a) Frequency domain diagram of pressure pulse signal under different conditions; (b) Frequency variation curve of corresponding pulse signal when well deviation; (c) Relationship curve between well inclination and overflow area, turbine rotor speed and signal frequency.

The time-domain change curves of pressure intensity at different speeds can be obtained, as well as the frequency-domain graphs of the turbine under different drilling fluid flow rates. Then, the frequency and amplitude of the signal can be analyzed.

4.2. Fluid simulation analysis of pulse generator

Fig. 10 shows a rotation of the turbine during the simulation process, and the corresponding valve block is transferred to each

coded hole pressure change cloud map. As the flow of drilling fluid increases, the turbine speed is increased and the flow is close to linear relationship. The rotational speed of the turbine increases with the opening area of its upper inlet D_i . With the increase of drilling fluid flow rate, the difference between different sizes of the turbine inlet flow channel D_i becomes greater, indicating that the linear variation under the control of the well deviation sensing pendulum can directly establish a linear relationship with the turbine speed as shown in Fig. 11.

Figs. 12 and 13 present the pressure variations monitored at turbine inlet (position 2) under pulse generator conditions of 15 and 20 L/s, respectively. The analysis focuses on three different turbine inlet flow channels (D_i) and corresponding monitoring points. The observed pressure fluctuations at the inlet remain relatively insignificant, as the pressure pulse signals maintain stable oscillation patterns. This phenomenon is primarily attributed to disturbances in the drilling fluid caused by pulse signals generated at the coded disk.

With increasing drilling fluid flow rate, the pressure amplitude at all monitoring points shows corresponding enhancement, while maintaining consistent waveform characteristics across measurement locations. Under constant flow conditions, the pressure values exhibit a gradual decrease with increasing turbine rotation speed. This occurs because the drilling fluid flow primarily drives turbine rotation, with pressure losses being predominantly consumed by the turbine's rotational energy.

Figs. 14 and 15 demonstrate consistent waveform patterns for the pressure pulse-coded signals at 25 and 30 L/s, aligning with the trends observed in prior analyses. As the turbine inflow diameter increases, the pressure amplitude at the inlet, in and outlet monitoring points of the pulse generator shows a gradual declining trend. Flow rate dominates the magnitude of pressure pulse signals. The figures further illustrate repetitive pressure pulse waveforms across three consecutive cycles, maintaining phase consistency throughout varying flow conditions. This waveform stability enhances signal integrity during long-distance transmission. At 30 L/s, the maximum pressure amplitudes recorded at the outlet monitoring point for different inflow diameters D_i measure 1.85, 1.64, and 1.51 MPa respectively.

4.3. Pressure pulse signal identification

Fig. 16(a) presents a Fourier analysis of the frequency-amplitude relationship in pressure-coded signals under varying drilling fluid flow rates and turbine inlet dimensions. Under constant system flow conditions, the amplitude-frequency relationship exhibits near-linear proportionality. The signal frequency and amplitude characteristics correlate with the rotational speed of the turbine valve block mechanism, and the well deviation can be calculated. Notably, the frequency and amplitude features remain distinguishable despite signal attenuation during transmission. This distinctiveness ensures reliable identification of pressure-coded signals even under energy loss conditions.

Measurement accuracy constitutes the critical performance parameter for mechanical well-deviation measurement systems. This accuracy is predominantly governed by the flow measurement precision of the turbine rotor. To enhance system calibration, we expanded the pulse-generator simulation matrix to include four distinct inlet diameters (D_i) corresponding to well deviation of 24°, 27°, 33°, and 36°. As evidenced by the computational fluid dynamics results in Fig. 16(b), the generated pulse signal frequencies measure 3.5, 3.78, 4.05, and 4.1 Hz for these respective well deviation angles. Notably, the frequency corresponding to the 30° well deviation angle registers at 3.85 Hz, while the 24° and 27° cases exhibit symmetrical distribution about the linear regression

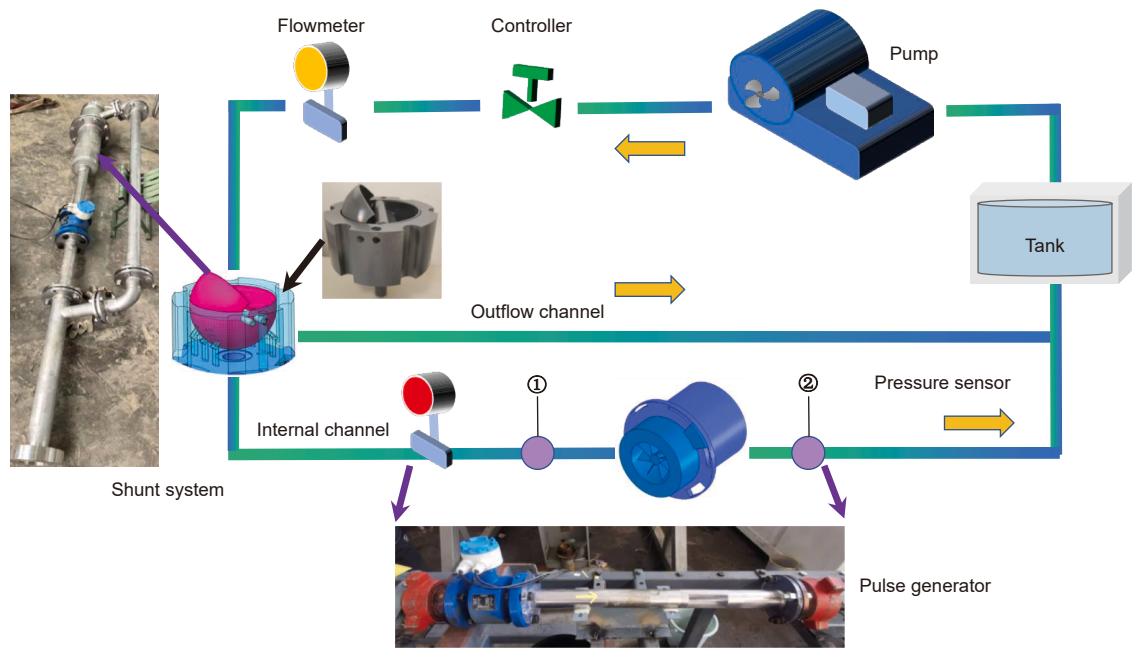


Fig. 17. Circulating pipeline test system.

Table 8
The structure and theoretical design parameters of the experimental prototype.

Parameter	Values	Parameter	Values
Diameter, mm	DN50	Maximum pump flow rate	35 L/s
Diameter of the branch pipeline	DN25	Maximum well deviation adjustment angle	90°
Flowmeter measurement accuracy	±1.0%	Measurement accuracy of pressure sensors	0.1% FS
Measurement range of the flowmeter	4–140 m ³ /h	Measurement range of the pressure sensor	0–5 MPa
Sampling frequency	1000 Hz	Pipeline connection form	Flange

line. The coefficient of determination R^2 for linear fitting is 0.965. This result proves that there is a highly linear positive correlation between frequency and amplitude. This nonlinear behavior primarily stems from two factors: (1) the inherent flow sensitivity of the turbine mechanism, and (2) the influence of the system's internal configuration on fluid flow dynamics.

Through theoretical calculation and simulation analysis, the corresponding relationship between well deviation and overflow area, turbine rotor speed and signal frequency is shown in Fig. 16(c). The ground signal acquisition end can determine the well deviation of the measured pulse signal through the changes of the four parameters.

4.4. Experimental verification

To verify the above-mentioned inclined flow control structure of the well and the functionality of the turbine pulse generator, a cyclic loop experimental system as shown in Fig. 17 was designed. The working process of the experimental system is as follows: When the tilt angle of the control well changes, the bias sensing module on the main line distributes the flow under the action of gravity, and the shunt system directs one branch of the flow to the turbine pulse generator. Pressure sensors are installed in the experimental system to monitor pressure pulse signals. Flow sensors and rotational speed sensors are set up, which are respectively used to monitor the changes in the flow of each branch and the changes in the turbine rotational speed. The information of the experimental equipment is shown in Table 8.

During the experiment, when the well deviation was set at 90°, 60° and 30°, the data such as the pressure pulse signal of the well deviation of the experimental system and the flow were measured. The flow rates were set at 30, 25, 20 and 15 L/s to analyze the variation characteristics of the key components of the mechanical well deviation measurement system under different flow rates.

Fig. 18(a) displays the raw mud pulse signal generated by the turbine-driven pulse generator during experimental operation. The data reveal that the eccentric structural design induces regular pressure fluctuations in the turbine pulse generator. Since the noise in the signals collected in the hydraulic circulation experiment system mainly comes from the high-frequency noise generated by the mud pump, low-pass filtering processing is adopted here to remove the noise interference. Fig. 18(b) shows the denoised mud pulse coding waveforms at different flow rates within a single operation cycle. The data demonstrate a direct proportionality between flow rate magnitude and pressure pulse amplitude, with higher flow conditions producing significantly enhanced signal intensities. The pressure loss generated by the tool during the experiment was 3 MPa.

The flow variation curve controlled by the counterweight stabilizing platform with the change of well slope is shown in Fig. 18(c). The flow distribution changes nearly linearly with the change of well deviation angle, verifying the reliability of the counterweight diversion structure design method. Under different flow rates, the variation law of the turbine speed was basically the same as that of the simulated turbine speed. As shown in Fig. 18(d), under different flow rates, the variation law of the turbine speed is basically

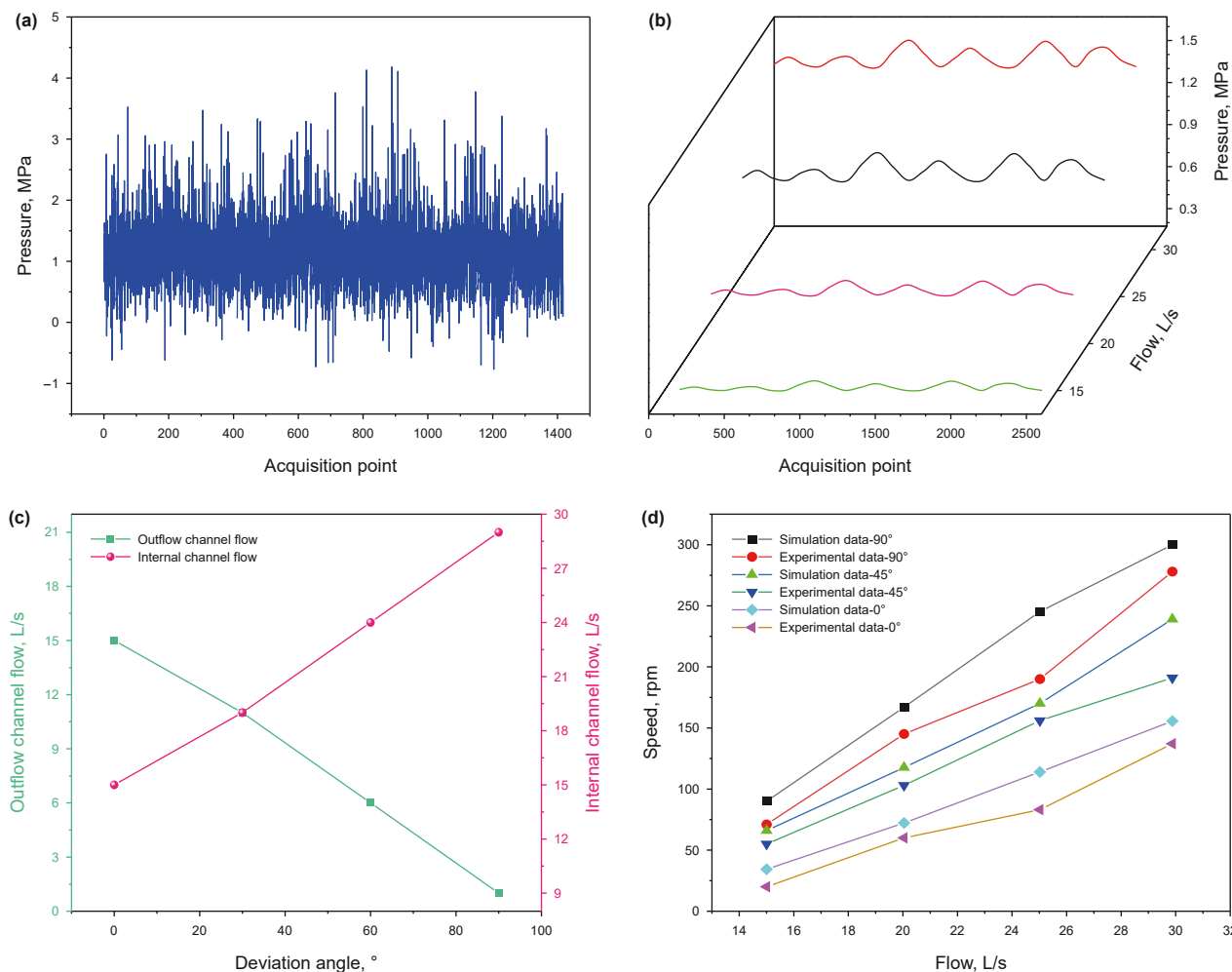


Fig. 18. Experimental signal characteristics. (a) Noisy pulse signal; (b) Pulse signals under different flow rates; (c) Pipeline diversion variation curve; (d) Comparison of experimental and simulated rotational speeds.

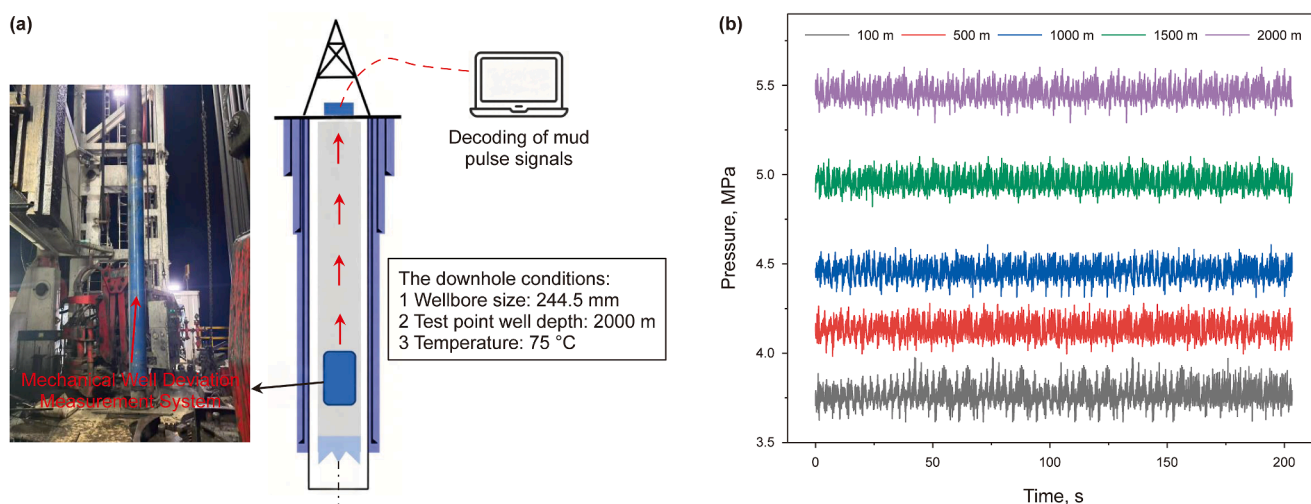


Fig. 19. Introduction to the field experiment and the collected effective signals. (a) Depicts the schematic diagram of the downhole testing structure; (b) Effective original signal.

consistent with that of the simulated turbine speed. With the increase of flow rate, the rotational speed of the turbine gradually increases and shows an approximately linear change law, which is

conductive to distinguishing the well deviation information. The rotational speed of the turbine in the simulation is higher than the measured rotational speed value in the experiment. This is because

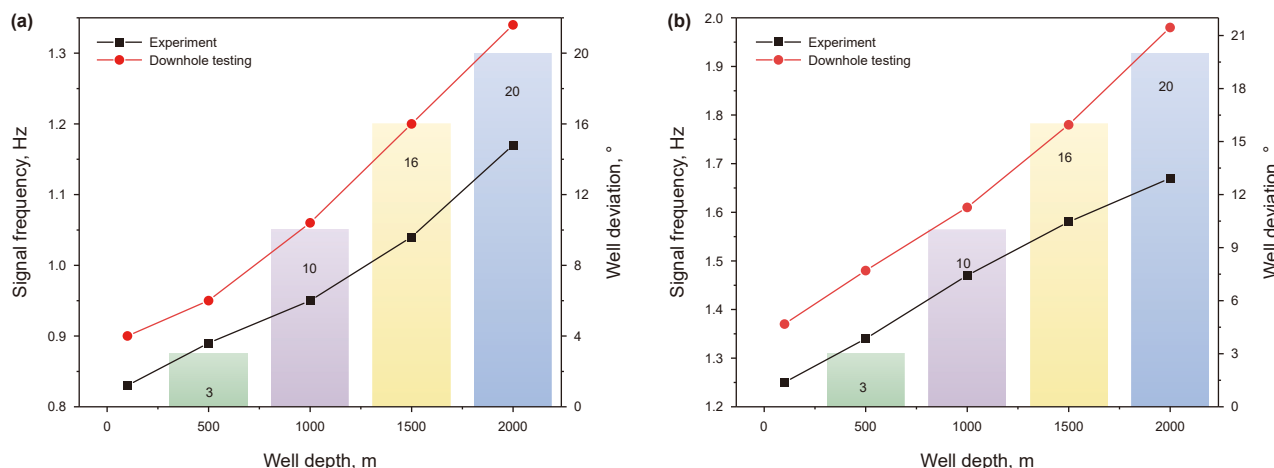


Fig. 20. Signal frequency and well deviation characteristics. (a) Flow rate of 20 L/s; (b) Flow rate of 25 L/s.

the internal flow field of the turbine structure is more stable in the simulation than in the experiment, and in the experiment, the turbine speed decreases due to frictional resistance.

To evaluate the mechanical transmission efficiency, in both indoor and underground experiments, when the flow was 25 L/s, the speed fluctuations in both were quite obvious. The simulation speed is 235 rpm and the experimental speed is 195 rpm. Therefore, the maximum speed loss of the turbine is 17%. Combining Eqs. (1) and (3), the maximum value of the turbine friction torque of the indoor experimental system can be obtained as 7.5 N·m. In the future, the impact of frictional resistance on turbine performance can be further reduced through structural optimization.

5. Testing in well

Based on the dual-component experimental system of well deviation sensing and well deviation signal generation structure, an engineering prototype of mechanical well deviation measurement was developed. The whole machine was made of erosion-resistant materials and downhole experimental analysis was carried out. The testing procedure is illustrated in Fig. 19(a). The experiment was conducted during drifting operation, engineering prototype was deployed near the drill bit end in the drill string assembly without MWD and downhole power drilling tools. Mud pulse pressure signals were collected at the standpipe. Summary of downhole conditions: Testing points are located at well depths of 400, 800, 1200, 1600, and 2000 m. The wellbore size is 311.1 mm, the casing size is 244.5 mm, the downhole temperature at the testing point is 55 °C. The corresponding well deviation range is 0–20°. A water-based mud was selected as the drilling fluid, with a density of 1.9 g/cm³ and a viscosity of 15 mPa·s. The drilling fluid flow rates were set to 20 and 25 L/s.

During the measurement process, it is necessary to raise the drill pipe by 2–3 m to ensure that the drill bit does not come into contact with the bottom of the well, and avoid stick-slip and vibration issues that may interfere with the stability of the downhole tool. Drilling was stopped at each measurement point. The mud pump flow rate and the solid-control grade of the drilling fluid were regulated to minimize the impact of particulate impurities on the downhole tools. As illustrated in Fig. 19(b), the mud pulse signal was acquired at the surface. The mud pulse signal carrying encoded information is susceptible to noise interference. The main noise source is the high frequency noise of the mud pump. Effective mud pulse signals are obtained by adopting the

method of composite filtering. The frequency characteristics of the effective pulse signal after denoising are analyzed by using the Fourier transform method.

Fig. 20(a) shows the frequency values obtained at different measurement points when the drilling fluid flow rate is 20 L/s. Different frequencies correspond to the well inclination angles at different measurement point positions. It can be found from the curve that the variation of the well deviation can be clearly identified through the frequency characteristics of the signal, verifying the feasibility of the design mechanism of the mechanical well deviation measurement system. Compared with the results of the indoor experiments, the signal frequency generated by the turbine pulse generation structure during the underground experiment is higher than the frequency value of the indoor experiment signal. This is because during the well experiment, the density of the drilling fluid is relatively high, and the pressure value in the internal flow channel of the instrument is large, which causes the turbine speed to increase. The maximum frequency difference between the two is 0.16 Hz. During the experiment, the maximum error between the mechanical well deviation measurement angle and the actual well deviation was 2.6°.

Fig. 20(b) shows the signal frequency variation curves obtained at each measurement point when the drilling fluid flow rate is 25 L/s. At the same measurement point position, as the drilling fluid flow rate increases and the turbine speed increases, the signal frequency also increases. This variation pattern is consistent with the conclusion of the aforementioned research. The comparison between the indoor experimental results and the downhole experimental results shows that the frequency difference of the maximum well deviation signal is 0.32 Hz. Compared with the effect of flow rate variation, the maximum difference in the frequency of the well inclination angle at the same measurement point is 0.65 Hz, that is, at the position with the maximum well inclination angle. It can be estimated through the curve that as the well depth and flow rate increase, the rate of change of the signal frequency will gradually increase. During the experiment, the maximum error between the mechanical well deviation measurement angle and the actual well deviation was 2.3°.

6. Conclusions

To address the operational limitations of conventional measurement tools in extreme environments typical of hot dry rock

formations and ultra-deep drilling, this study develops a fully mechanical well-deviation measurement system. Through integrated numerical modeling, computational fluid dynamics (CFD) simulations, and laboratory validation tests, we systematically analyzed the system's measurement accuracy and operational stability. Our experimental results confirm the technical feasibility of this mechanized deviation measurement system, yielding the following critical conclusions:

- (1) The fully mechanical well deviation measurement system developed in this study achieves inclination measurement through an innovative mechanical design. The system utilizes a double-offset structure that detects well deviation and translates it into flow rate variations, effectively converting effectively information into measurable parameters. Analysis reveals that the response accuracy of the offset block is related to the frictional resistance of the connection structure and its size and material. This study innovatively combines the turbine with the pulse generator. Due to the turbine's sensitivity to flow changes, it can identify variations in inclination and further generate mud pulse signals with amplitude-frequency variations.
- (2) The numerical results are in good agreement with the experimental results. The pressure amplitude and rotational speed parameters obtained from the simulation calculation are larger than the experimental results. The maximum velocity loss is 17%, which is because kinetic energy and thermodynamic losses were not considered in the simulation calculation. The experimental results show that the well deviation signal can be effectively presented through the amplitude-frequency characteristics of the pulse signal. This system can overcome errors through structural optimization in the later stage to improve measurement accuracy.
- (3) The flow rate is the key factor affecting the strength of the pressure pulse signal. The more obvious the amplitude change between the coded signals, the less distortion of the coding characteristics of the signal in transmission is ensured, and the identification degree of the signal in time domain is improved. The structure of the pulse generator can be optimized to further improve the signal identifiability under well deviation control.
- (4) In the practical application process, the signal frequency is disturbed by various factors. In the well descent experiment, the maximum measurement error of well deviation was 2.6°. The next step of research can establish signal compensation and correction methods to ensure the stability of signal generation and the accuracy of identification.

In future work, the measurement accuracy and reliability can be further improved by optimizing the structure, coding methods and signal recognition algorithms. In addition, under conditions of high temperature, high pressure and different drilling fluid performance, comprehensive tests were conducted on the measurement accuracy, thermodynamic properties and material stability of the system.

CRediT authorship contribution statement

Qi-Long Xue: Supervision, Resources, Funding acquisition. **Jun Qu:** Data curation, Conceptualization. **Jin Wang:** Resources, Formal analysis. **Xing-Yu Tan:** Validation, Methodology. **Chong Wang:** Visualization, Validation. **Ya-Feng Li:** Software, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

- Bulant, P., Eisner, L., Pšencík, I., Calvze, J.L., 2007. Importance of borehole deviation surveys for monitoring of hydraulic fracturing treatments. *Geophys. Prospect.* 55 (6), 891–899. <https://doi.org/10.1111/j.1365-2478.2007.00654.x>.
- Caruzo, A., Hutin, R., Reyes, S., Tweel, A., Temple, P., 2012. Advanced design and execution techniques for delivering high data rate MWD telemetry for ultra-deep wells. In: OTC Arctic Technology Conference. OTC-23749-MS. <https://doi.org/10.4043/23749-MS>.
- Chatterjee, K., Dick, A., Grimmer, H., Herlitzius, J., Otto, M., Klotzer, S., Epplin, D., Schroder, J., Macpherson, J., 2014. High-temperature, 300 °C directional drilling system including drill bit, steerable motor, and drilling fluid. *GRC Trans.* 38, 245–248. <https://api.semanticscholar.org/CorpusID:245668145>.
- Chen, M., 2017. Structure Design and Optimization of Mud Pulse Generator. Doctoral Dissertation, Changjiang University, Wuhan, China.
- Fossa, M., Guglielmini, G., 2022. Pressure drop and void fraction profiles during horizontal flow through thin and thick orifices. *Exp. Therm. Fluid Sci.* 26 (5), 513–523. [https://doi.org/10.1016/S0894-1777\(02\)00156-5](https://doi.org/10.1016/S0894-1777(02)00156-5).
- Gao, X., Li, T., Zhang, Y., Kong, X., Meng, N., 2022. A review of simulation models of heat extraction for a geothermal reservoir in an enhanced geothermal system. *Energies* 15 (19), 7148. <https://doi.org/10.3390/en15197148>.
- Giosio, D.R., Henderson, A.D., Walker, J.M., Brandner, P.A., 2017. Physics-based hydraulic turbine model for system dynamic studies. *IEEE Trans. Power Syst.* 32 (2), 1161–1168. <https://doi.org/10.1109/TPWRS.2016.2574330>.
- Han, H., Xue, L., Fan, H., Liu, X., Liu, M., Wang, Z., 2022. Analysis of pressure wave signal generation in MPT: an integrated model and numerical simulation approach. *J. Petrol. Sci. Eng.* 209, 109871. <https://doi.org/10.1016/j.petrol.2021.109871>.
- Li, H., Liang, J., Li, C., Li, G., Meng, Y., Yang, P., Liu, J., Xu, L., 2022. A novel method to improve mud pulse telemetry performance during gaseated underbalanced drilling. *J. Petrol. Sci. Eng.* 213, 110400. <https://doi.org/10.1016/j.petrol.2022.110400>.
- Liu, H., Wang, W., Wen, Y., Hao, L., Wang, W., Mi, H., 2019. A novel axial flow self-rectifying turbine for use in wave energy converters. *Energy* 189, 116256. <https://doi.org/10.1016/j.energy.2019.116256>.
- Liu, X., Sun, W., Song, W., Li, Q., Zhu, C., 2022. Development and application of a high temperature wired measurement while drilling system. In: *ISMSEE 2022; the 2nd International Symposium on Mechanical Systems and Electronic Engineering*. IEEE, pp. 1–5.
- Lunney, I., Duriez, A., Solbakk, T., Skaug, M.B., Brian, T., 2017. Harsh environment logging-while-drilling tools enhance well performance in North Sea HPHT wells. In: SPE Europe Energy Conference and Exhibition. SPE 185866-MS. <https://doi.org/10.2118/185866-MS>.
- Ma, T., Chen, P., Zhao, J., 2016. Overview on vertical and directional drilling technologies for the exploration and exploitation of deep petroleum resources. *Geomech. Geophys. Geo-Energy Geo-Resour.* 2 (4), 365–395. <https://doi.org/10.1007/s40948-016-0038-y>.
- Noureddin, A., Irvine-Halliday, D., Mintchev, M.P., 2002. Accuracy limitations of FOG-based continuous measurement-while-drilling surveying instruments for horizontal wells. *IEEE Trans. Instrum. Meas.* 51 (6), 1177–1191. <https://doi.org/10.1109/TIM.2002.808025>.
- Qu, J., Xue, Q., Wang, J., Sun, J., Lu, J., 2024. From design to experimental validation of the fully mechanical gravity tool face measurement-while-drilling system. *SPE J.* 29 (6), 2971–2987. <https://doi.org/10.2118/219480-PA>.
- Reich, M., Oesterberg, M., Montes, H., Treviranus, J., 2003. Straight down to success: performance review of a vertical drilling system. In: SPE Annual Technical Conference and Exhibition. SPE, pp. 84451–MS. <https://doi.org/10.2118/84451-MS>.
- Salamon, R., Kaminski, H., Fritzkowski, P., 2020. Estimation of parameters of various damping models in planar motion of pendulum. *Meccanica* 55 (9), 1655–1677. <https://doi.org/10.1007/s11012-020-01197-z>.
- Xu, H., Li, T., Wang, W., Liao, L., 2017. Discussion on sawtooth wave pressure fluctuation of hydraulic machinery. *Mech. Electr. Techn. Hydropower Stat.* 40 (5), 7–10+100. <https://doi.org/10.13599/j.cnki.11-5130.2017.05.002> (in Chinese).
- Xue, Q., Wang, R., Sun, F., Huang, L., Han, L., 2014. Continuous measurement-while-drilling utilizing strap-down multi-model surveying system. *IEEE Trans. Instrum. Meas.* 63 (3), 650–657. <https://doi.org/10.1109/TIM.2013.2282412>.

- Yan, Z., Xu, W., Ai, C., Geng, Y., 2019. Parametric study on pump noise processing method of continuous wave mud pulse signal based on dual-sensor. J. Petrol. Sci. Eng. 178, 987–998. <https://doi.org/10.1016/j.petrol.2019.04.018>.
- Yang, N., Yan, Z., Yin, X., Jia, M., Geng, Y., 2022. Mathematical modeling and experimental investigation of a rotary valve generating sinusoidal pressure signals based on fan-arc-straight orifice. J. Petrol. Sci. Eng. 209, 109807. <https://doi.org/10.1016/j.petrol.2021.109807>.
- Yi, M., Kim, J., Son, J., 2009. Borehole deviation effect in electrical resistivity tomography. Geosciences J. 13 (1), 87–102. <https://doi.org/10.1007/s12303-009-0008-2>.