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Research on Drilling Bit Positioning Strategy Based on SINS MWD System

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ABSTRACT Accurate measurement of drill bit position and direction is the main technology to realize automation and intelligence in oil drilling field. In recent years, with the rapid development of complex drilling technologies such as high deviation wells, directional wells and horizontal wells, higher requirements have been put forward for measurement technology, especially for real-time monitoring of bit attitude and position during the drilling process. Therefore, for the past few years, the measurement while drilling (MWD) system has been widely recognized and developed rapidly in precision targeted drilling. among them, strap-down inertial navigation system (SINS) consisting of accelerometer and gyroscope is the key of down-hole measurement while drilling. To solve the problem of accumulated errors in SINS, in this paper, a positioning error correction method based on kinematic constraint-aided (KC) SINS zero velocity updated (ZUPT) model is proposed. Firstly, based on the acceleration and angular velocity information measured by SINS, empirical mode decomposition (EMD) and wavelet de-noising reconstruction are performed for MWD signals. Secondly, the static detection model of the drill bit is established by using the reconstructed signal. Thirdly, using drilling technology to analyze the motion attitude of the bit, the KC model of the down-hole bit is established. By analysis the alternating effect of the KC model and the ZUPT model in the process of the bit movement and stop, the ZUPT model of the SINS is established. Finally, experimental verification is performed by building a drilling platform. The experimental results show that the maximum positioning error of the proposed positioning model is 0.15 m within 300 s. Comparing with a single KC model and a single ZUPT model, the bit positioning accuracy is improved to 92.6%, which effectively suppresses the original cumulative error, and verifies the feasibility of the proposed method.

INDEX TERMS Measurement while drilling system, strap-down inertial navigation system, empirical mode decomposition, kinematic constraint-aided, zero velocity updated.

I. INTRODUCTION

Petroleum is called "black gold" which belongs to fossil fuel and is non-renewable [1]. It is one of the most important energy sources for the development of today's society [2]. Since the mid-19th century, when people began to extract oil from the ground, oil has been indispensable to industries, agriculture and national defense as well as to food, clothing, shelter and transportation for everyone. With the growth of the world economy, the demand for oil is increasing [3], [4]. Although clean and renewable energy accounts for an increasing proportion of the world's energy, oil is still the most important driving force for world progress. The constantly decreasing in petroleum has put forward higher requirements for current mining technology [5].

At present, the direction of global petroleum exploration and development comes from conventional reservoirs to low permeability and unconventional reservoirs, from land to ocean, from shallow to deep and ultra-deep reservoirs [6], [7]. Oil and gas resources to be developed in the world mainly concentrated in low permeability, deep reservoirs, marine reservoirs and unconventional reservoirs [8].The worse the reservoir quality, the greater the demand for engineering technology [9]. Facing the situation of "low"(low pressure,

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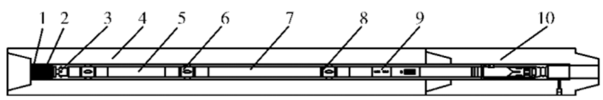
low permeability, low abundance), ‘‘deep’’(deep oil wells), ‘‘sea’’(offshore oil and gas fields), ‘‘non-conventional’’(shale gas, dense oil, dense gas) and ‘‘new’’(combustible ice, geothermal) encountered in the process of oil and gas exploitation, as well as the severe situation of new fields such as marine carbonate reservoirs and late development of ultra-high water cut oilfields, engineering technology has met new challenges, and has also obtained rare development opportunities [10], [11].

Looking at the development trend of drilling technology, drilling is undergoing profound changes [12], [13]. Exploration and development of extreme environmental resources are becoming a hot spot and focus [14]. With the increase of mining depth and the change of down-hole conditions, the existing drilling measurement methods can not meet the need of complex wells. Since the late 1960s, MWD technology has developed rapidly in the field of drilling [15]. It is used for real-time formation evaluation and drilling geological guidance. It also shows economic and technical advantages in controlling bit trajectories in horizontal wells or highly deviated wells and complex logging environments [16], [17].

In this case, the MWD system based on micro-inertial measurement unit has been developed, and widely recognized in oil field exploitation because of its advantages of low cost, small size, long life, high integration, strong impact resistance and high reliability [18]. Through real-time measurement of bit acceleration and angular velocity during drilling, the MWD system can calculate drilling tool posture, measure wellbore trajectory, invert bit position and evaluate formation drill-ability through algorithm, and realize accurate measurement of borehole azimuth, deviation angle, tool face angle and well depth position, so as to ensure that the wellbore moves smoothly to the target reservoir [19], [20].

The micro-inertial measurement unit uses a SINS to measure the attitude angle and acceleration of the object. A SINS consists of three single-axis accelerometers and three single-axis gyroscopes [21]. The accelerometer measures the three-axis acceleration signal of the object in the carrier coordinates in real time, while the gyroscope measures the angular velocity signal of the carrier relative to the navigation coordinate system in real time. Then the attitude of the object is calculated. Because of the advantages of SINS, it has a broad application prospect in both civil and military positioning fields. However, due to the gyroscope’s components in inertial devices, there are accumulated systematic errors, and the errors will gradually increase with time. So it is very important to suppress angular velocity drift. At present, many international scholars have proposed different compensation methods for the error of inertial devices, such as Suij’s position recursive estimation method based on least squares to reduce the error [22]. Liu *et al.* adopted the second harmonic demodulation scheme of light-emphasized modulation signal to compensate for laser intensity fluctuation in fiber optic gyroscope [23]. Fontanella *et al.* used an artificial neural network as their compensation methods [24]. The improved polynomial fitting method is used to calibrate the temperature of the Micro-Electro-Mechanical System gyroscope, but these methods require additional sensors, which on the one hand increase the cost, on the other hand not be applied under various down-hole interference conditions. In the process of drilling, the working environment of the bit is very complex, and it will be affected by many kinds of vibration and noise, which seriously affects the accurate positioning of the bit. Therefore, removing noise interference, improving signal-to-noise ratio and restoring real signals as far as possible are the main points of data preprocessing while drilling.

With the gradual application of the MWD system in the field of petroleum exploration, the research of MWD system has been deepened gradually. In the research of inversion of bit position using the MWD signal while drilling, different scholars have put forward their own research schemes, such as Yang *et al.*’s navigation scheme based on non-holonomic constraints and steady component constraints of bit [25], Zheng *et al.*’s integrated empirical mode decomposition (EMD) for MWD signal and design based on it [26]. Different low-pass filtering methods of intrinsic mode function, Li *et al.* studied the noise reduction and signal extraction of MWD drilling mud signal based on pulse code information [27]. Yao *et al.* application ZUPT model in integrated navigation [28]. DeSanto *et al.* applied KC algorithm to ship navigation data processing [29]. However, these researches not put forward the corresponding technical scheme for precise positioning a bit after de-noising of down-hole while drilling signal. Therefore, this paper proposes a de-noising algorithm based on EMD and wavelet packet reconstruction for down-hole measurement signals while drilling, and then uses the reconstructed signals to alternate KC and ZUPT models to achieve dynamic real-time positioning of down-hole drills.



1. Adjusting gasket 2. Shock absorber 3. Upper end 4. Drill collar 5. Power supply 6. Centralizer assembly 7. Exploratory tube 8. Centralizer assembly 9. Pulse generator 10. Suspension short section assembly

FIGURE 1. Down-hole measurement section of MWD system.

II. MEASUREMENT WHILE DRILLING SYSTEM

The MWD system consists of the ground part and the down-hole part. The ground part mainly includes host computer, driller’s display, signal separator, computer and pressure sensor. Its function is to receive down-hole measurement information, decode and plot, to provide directional well engineers and drillers with timely understanding of down-hole drilling tool surface and engineering parameters, to provide basis for drilling decision-making and operation, and to realize trajectory control. The down-hole part mainly consists of drill collar, suspension section, pulse generator, gyro tube, battery pack, centralizer and shock absorber, as showed in Figure 1.

In the inertial MWD system, the gyroscope tube is the core component of the whole system, which mainly consists of measuring section, shock absorber, plug, transition tube and compression tube. The measurement section is composed of a two-axis gyroscope sensor and a three-axis accelerometer, and the fiber optic gyroscope is used. Fiber optic gyroscope is a solid-state gyroscope, which has better vibration resistance than flexible gyroscope and is suitable for drilling engineering environment.

In the past ten years, progress of MWD technology divided into three aspects. The first is that it has the ability of logging while drilling and geological guidance. The second is to make the sensor of directional measurement while drilling and logging tool closer to the bit, so that data can be acquired faster and more accurately, thus improving the accuracy and ability of real-time decision-making of the well site. Thirdly, electromagnetic wave data transmission technology has been rapidly developed and applied. At present, drilling fluid pulse is widely used to transmit measurement data in the international MWD system. This technology works stably and reliably. It is a common drilling tool and plays an important role.

At present, in petroleum drilling engineering, because the blind area of conventional gamma-ray while drilling is too long, the lithologic lag phenomenon of formation can not be judged in time, and the muddy interbed can not be found in time when drilling in horizontal section, which leads to the bit easily drilling out of the reservoir, and the trajectory needs to be adjusted frequently. The MWD system can dynamically and accurately obtain the gamma and deviation data at the bit, which can compensate for the shortcomings of conventional gamma geological steering tools during drilling. The ground software system is used to make the proper interpretation and decision to implement MWD and trajectory control.

III. ANALYSIS OF DOWN-HOLE DRILLING BIT LOCATION MODEL

By real-time measuring the acceleration and angular velocity near the bit in the process of drilling, the inertial measurement while drilling system obtain the inclination angle θ, tool face angle φ and azimuth ψ of the drilling tool to calculate the posture of the drilling tool and evaluate the wear of the bit and invert the geological information of the bit location. Figure. 2 shows the transformation of three angles from the carrier coordinate system to the earth coordinate system. The information transmission between underground and ground is the key technology in MWD. The technology can be used to monitor the well trajectory in real time. Therefore, the reliability of information transmission will directly affect the operation results of the whole closed-loop control system.

During the inertial MWD, the measured bit motion signal contains various interference vibration noise, which seriously affects the use of the signal while drilling. Therefore, removing noise interference, improving signal-to-noise ratio and restoring real signals as far as possible are the key points of data preprocessing while drilling. When drilling in different

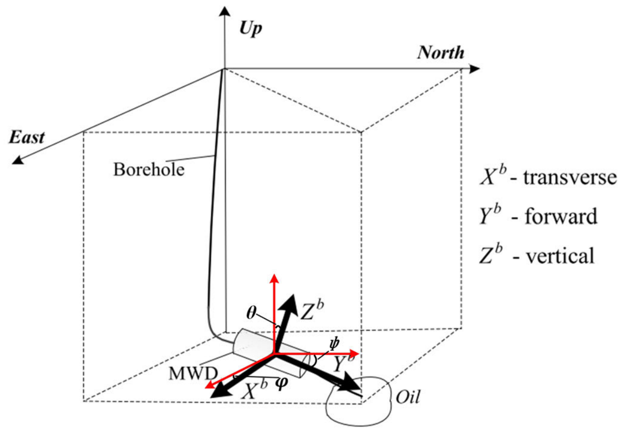


FIGURE 2. Diagram of relationship between bit coordinate system and earth coordinate system.

strata, the vibration signal of drill bit is a non-stationary time-varying signal, so the measurement signal while drilling is a non-linear and non-stationary signal. In addition, gyroscope is the main measurement component of MWD system, but gyroscope drift, long time cumulative calculation will produce comparatively large errors, so a kind of algorithm is used to estimate and compensate gyroscope drift. In the process of drilling, besides minimizing the influence of random factors, it is necessary to calculate drilling data and correct the drift generated by the algorithm.

Due to a series of phenomena such as wide noise source, strong energy, low signal-to-noise ratio of bit vibration signal and gyroscope drift, a measurement error correction strategy for MWD system based on empirical mode decomposition and kinematics constraints is proposed in this paper. To the basic measurement deviation problem of gyroscope and accelerometer, EMD is used to separate the valid data from noise. The signal after separated is de-noised and reconstructed by wavelet. Over reconstructed signal judgment static state detection, SINS ZUPT strategy based on Kalman Filter model and KC aided method is adopted to research bit positioning error.

A. DE-NOISING AND RECONSTRUCTION OF SIGNAL WHILE DRILLING

In the process of inertial MWD, SINS in MWD system measures the motion signal of drill bit accompanying, a lot of noise interference. There are four sources of noise as follows. Firstly, vibration caused by rotating disc. The rotating disc causes intensive vibration, which be transmitted to the bit through the drill string. This interference will periodically be related to the speed. Secondly, in the process of drill string rotation, because the drill string is unbalanced and not in the middle, it may cause the contact and collision between the drill string and the borehole wall, which is produce friction vibration, and then affect the vibration of the drill bit. Thirdly, other mechanical vibration. The mechanical vibration caused by the sway of the derrick, the diesel engine, and generate through the derrick and the drill string to drill bit. Fourthly, the measurement error of the inertial sensor itself and the error introduced in the signal transmission process. So in order to get the measurement signal without noise interference, the signal must be decomposed and reconstructed first, and then the follow-up steps can be carried out.

The vibration signal of the bit while drilling is a kind of non-linear and non-stationary signal. EMD decompose the non-linear and non-stationary signal into several linear steady-state eigenfunction according to the different time scales of the signal. EMD obtained by the basis function from the signal itself. So it's has good adaptability. However, only using EMD decomposition to deletes high-frequency components also delete part of the bit vibration signal. This paper presents a method of de-noising while drilling measurement signals by combining EMD and wavelet packet de-noising. First, the non-linear and non-stationary signals are decomposed into linear and steady intrinsic mode function (IMF) components by using the advantages of EMD, then the main noisy IMF components are accurately identified according to the characteristics of signal autocorrelation function. Finally, the mixed signals and noises in noisy IMF components are separated and reconstructed by using wavelet packet de-noising method.

EMD is used to decompose the measurement signal $x^{'}(t)$ with noise into N-order IMF modal components with frequencies ranging from high to low. The outstanding advantage of this method is that it has good data adaptability. Time series $x(t)$ is decomposed by EMD expressed as follows,

$$x\left(t\right)=\sum\nolimits_{i=1}^{n}c_i\left(t\right)+r_n(t) \tag{1}$$

where, In Eq. (1), $c_i\left(t\right)$ is the IMF component of different frequency band scales, $r_n(t)$ is the residual component of the decomposed signal, and n is the number of IMF components. EMD can decompose any signal into independent IMF functions. The decomposed IMF components are based on the local characteristic time scale of the signal itself. Each component represents the characteristics of the original signal at different time scales. EMD can decompose non-linear and non-stationary MWD signals into linear and stationary IMF components from high to low frequency without choosing appropriate basis functions.

In IMF components with frequencies ranging from high to low, noise generally concentrates on high frequency components. According to the characteristics of autocorrelation function of each IMF component, the main noisy IMF component is found. If $x(t)$ is a measurement signal while drilling, its autocorrelation function is as follows,

$$x_{corr}\left(\tau\right)=E[imf_i(t)imf_i(t+\tau)] \tag{2}$$

where, in Eq. (2), $x_{corr}\left(\tau\right)$ is the autocorrelation function and $imf_i(t)$ is the intrinsic mode function at different time. The autocorrelation function reflects the correlation degree of signal at different moments. According to the statistical characteristics of random noise, the autocorrelation function of random noise at zero point is the largest, and decay rapidly to near zero at the other time. Relatively speaking, the effective signal contains less noise, and its autocorrelation function also has the maximum value at the zero point. However, due to the existence of certain interrelationship, it will change regularly at other times, and it does not decay rapidly to zero. Therefore, according to the characteristics of the signal autocorrelation function, the IMF component with noise as the main component can be judged by calculating the autocorrelation function of each order IMF component.

Noise and useful signal in MWD measurement signal are mixed together. It is necessary to de-noise the determined IMF components. Wavelet packet de-noising method is suitable for processing this kind of mixed signal. Wavelet packet decomposition can not only decompose the low frequency part, but also decompose the high frequency part. The main noisy modal component imf_1—imf_k is de-noised by wavelet packet threshold, and each component $imf^{'}_1$—$imf^{'}_k$ after de-noising is obtained. The modal component after de-noising by wavelet packet and the rest of the components are reconstructed. Finally, the measurement signal $x'(t)$ after de-noising is obtained.

$$x(t)^{'}=\sum\nolimits_{i=1}^{k}imf^{'}_i+\sum\nolimits_{j=k+1}^{N}imf_j \tag{3}$$

B. DRILLING BIT STATIC STATE DETECTION

According to Newton's law, the acceleration and angular velocity information of the object itself directly reflect the motion state of the object. If we want to detect the state of the bit, we must first judge the measurement signal while drilling after de-noising. When the value of acceleration and angular velocity of the object is zero, the object is in a stationary state or a uniform linear motion state. However, due to the mechanical vibration of the bit itself, the limitation of the control accuracy of the motor traction speed regulation and the contact and collision between the drill string and the borehole wall, it is impossible for the bit to achieve uniform linear motion with zero acceleration and angular velocity. Therefore when the relative zero values of acceleration and angular velocity of the bit are stable in a certain threshold range for a period of time, it considered that the current bit is in a static state. Based on this feature, the static state of the bit can be detected in real time by using the measured values of the MWD system.

If the drilling pipe is in a static state, the acceleration vector measured by the MWD system approaches gravity acceleration g $=9.81$ m/s^2 and angular velocity vector approaches zero. According to this characteristic, three-axis acceleration and tri-axial angular velocity information obtained from strap-down inertial navigation system are calculated by vector modulus operation.

$$\left\|\boldsymbol{a}_k^b\right\|=\sqrt{\left(a_{x,k}^b\right)^2+\left(a_{y,k}^b\right)^2+\left(a_{z,k}^b\right)^2} \tag{4}$$

$$\left\|\boldsymbol{w}_{ib,k}^b\right\|=\sqrt{(w_{x,k})^2+(w_{y,k})^2+(w_{z,k})^2} \tag{5}$$

where, in Eqs. (4) and (5), $\|\boldsymbol{a}_k^b\|$ and $\left\|\boldsymbol{w}_{ib,k}^b\right\|$ are respectively expressed as vector modes of SINS acceleration and angular velocity, $\boldsymbol{a}_k^b$ denotes as acceleration in carrier coordinate system measured by SINS and $\boldsymbol{w}_{ib,k}^b$ as angular velocity measured by SINS. K is the sampling sequence of SINS, and its sampling period is $T = t_{k+1} - t_k$.

The judgment threshold of SINS acceleration is set to $S_{a,max}$ and $S_{a,min}$, satisfying $S_{a,max} > g > S_{a,min}$, and the judgment threshold of angular velocity is S_w. By judging the threshold value, acceleration and angular velocity collected at each moment are divided into two states which are in accordance with the static state and not in accordance with the non-static state. The mode $\|\boldsymbol{a}_k^b\|$ of acceleration must be satisfied between thresholds $S_{a,max}$ and $S_{a,min}$ in order to be considered as stationary.

$$A_1 = \begin{cases} 1, & S_{a,max} > \|\boldsymbol{a}_k^b\| > S_{a,min} \\ 0, & \text{Others} \end{cases} \tag{6}$$

The judgment formula for the static state of diagonal velocity as follows,

$$A_2 = \begin{cases} 1, & \left\|\boldsymbol{w}_{ib,k}^b\right\| < S_w \\ 0, & \text{Others} \end{cases} \tag{7}$$

where, in Eq. (6) and (7), A_1 and A_2 are the results of static state judgment of acceleration and angular velocity respectively. Only both A_1 and A_2 satisfy the static condition the drilling tool be considered to be in a static state.

$$A_i = A_1 \cap A_2 \tag{8}$$

Although the acceleration and angular velocity are decomposed and reconstructed in the previous step, the noise caused by mechanical vibration has been removed, but there is still a small amount of noise caused by the signal in the transmission process, which will lead to erroneous judgment under the influence of noise in the logic operation of static state judgment in the subsequent step. Therefore, A_i will cause salt and pepper noise in the process of judgment, which will affect the subsequent steps. So, it is necessary to filter the reconstructed signal effectively.

Among many filtering algorithms, median filtering is a kind of non-linear signal processing technology based on ranking statistics theory and can effectively suppress noise. The basic principle of median filtering is to replace the value of a point in the digital sequence with the median value of each point in a neighborhood of the point, so that the value of the surrounding elements is close to the true value, thus eliminating isolated noise points. Median filtering has a good filtering effect on impulse noise. Especially when filtering noise, it can protect the edge of the signal so that it is not blurred. Another reason for choosing the median filtering algorithm is that the proposed method needs to deal with a large number of real-time down-hole data. The median filtering algorithm can process data quickly. If other filtering algorithms are used, the data analysis will be delayed and the real-time bit trajectory can not be obtained. These excellent characteristics are not found in other linear filtering methods, so the paper uses median filtering algorithm for A_i, and then removes salt and pepper noise and obtains the logical parameter $A_{m,i}$ which can judge the static state stably.

$$A_{m,i} = f_{medianfilter}(A_i, l) \tag{9}$$

where, in Eq. (9) l is the filter window width of median filter. The flow chart of SINS static state judgment is shown in Figure 3.

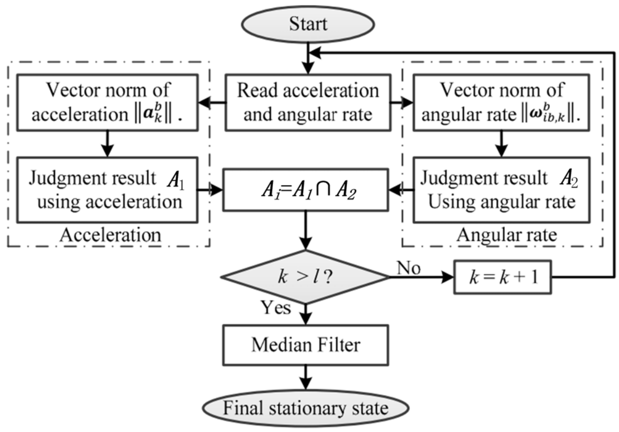


FIGURE 3. Flow chart for stationary state judgment processing.

C. DRILLING BIT ZUPT MODEL

The angular velocity measured by SINS is used to calculate the quaternion navigation, and three-axis attitude angle of the bit relative to the navigation coordinate system is obtained. The heading angle is ψ, the pitch angle is θ, and the roll angle is γ. Therefore, the attitude conversion matrix from the bit carrier coordinate system to the navigation coordinate system is as follows,

$$\boldsymbol{C}_b^n = \left(\boldsymbol{C}_n^b\right)^{\mathrm{T}} = \begin{bmatrix} c\psi c\theta & c\gamma s\theta s\psi - c\gamma s\psi & s\psi s\gamma + c\gamma c\psi s\theta \\ c\theta s\psi & c\psi c\gamma + s\psi s\theta s\gamma & c\psi s\gamma s\theta - c\gamma s\psi \\ -s\theta & c\theta s\psi & c\theta c\psi \end{bmatrix} \tag{10}$$

where, in Eq. (10), the alphabet "c" represents the cosine function "cos", and the alphabet "s" represents the sine function "sin".

The acceleration vector of SINS carrier coordinate system is $\boldsymbol{a}_k^b$, and the position calculation model of SINS can be simplified by Newton's second law, which can be transformed into the form of local navigation coordinate system. The local navigation coordinate system is cartesian coordinate system conforming to the right hand criterion. Set any point in the positioning space as the origin of the coordinate system, and the three coordinate axes point eastward, northward and antenna respectively. In the process of drilling, the distance of MWD is usually only 5 kilometers, and the key interval is less, which is only one part of the radius of the earth. In the process of positioning calculation, ignoring the influence of curvature and rotation can simplify the model and improve the efficiency of system operation. Therefore, the position calculation model of SINS in the navigation coordinate system expressed as follows,

$$a_k^n = C_b^n a_k^b - g^n \tag{11}$$
$$V_{k+1}^n = V_k^n + a_k^n dt \tag{12}$$
$$P_{k+1}^n = P_k^n + V_k^n dt \tag{13}$$

where, in Eq. (11), $g^n = [00g]^{\mathrm{T}}$ is gravity acceleration vector, a_k^n is drill acceleration vector in navigation coordinate system after removing gravity acceleration. V_k^n and P_k^n are velocity and position vectors in navigation coordinate system respectively, dt is sampling time interval before and after two times.

The ZUPT strategy of SINS is mainly a method to correct the positioning information of the carrier by taking advantage of the zero parking speed of the carrier in the course of movement and taking the velocity error as the observation quantity. Through the real-time static state detection method described above, after judging the bit state, when the bit is static, ZUPT model can better realize the error correction of SINS.

According to the bit position calculation model described in Eq. (10) to (12), it as follows,

$$\begin{cases} P_{k+1}^n = P_k^n + V_k^n T + \left(C_b^n a_k^b - g^n\right) T^2/2 \\ V_{k+1}^n = V_k^n + (C_k^n a_k^b - g^n) T \end{cases} \tag{14}$$

where, in Eq. (14), T is the sampling period of the positioning system. The total differential calculation under the parameters of Eq. (13) is carried out. The results of the differential calculation are as follows,

$$\begin{cases} \delta P_{k+1}^n = \delta P_k^n + \delta V_k^n T - \left(C_b^n a_k^b \times\right) \frac{T^2}{2} \delta A_k + C_b^n \frac{T^2}{2} \delta a_k^b \\ \delta V_{k+1}^n = \delta V_k^n - \left(C_b^n a_k^b \times\right) T \delta A_k + C_b^n T \delta a_k^b \end{cases} \tag{15}$$

where, in Eq (15), δP^n and δV^n are the position error vectors and velocity error vectors in the bit navigation coordinate system respectively δA is the attitude error vector, δa^b is the measurement noise of SINS accelerometer, and $a^b \times$ is the anti-symmetric matrix of the acceleration vector.

Therefore, the state vector of the system state equation is set as follows,

$$x_k = \left[\delta P_k^n \quad \delta V_k^n \quad \delta A_k\right]^{\mathrm{T}} \tag{16}$$

where, Eq. (15) can be expressed as follows,

$$x_{k+1} = F_{k,k+1} x_k + G_k W_k \tag{17}$$

where, in Eq. (17),W_k is the system noise vector of the equation of state, $W_k = [\omega_\varepsilon \delta a^b]_k^{\mathrm{T}}$, ω_ε is the measurement noise of SINS gyroscope, G_k is the one-step transfer matrix of system noise and $F_{k,k+1}$ is the one-step transfer matrix of state vector.

$$F_{k,k+1} = \begin{bmatrix} I_{3\times3} & T \cdot I_{3\times3} & -\left(C_b^n a^b \times\right) T^2/2 \\ 0_{3\times3} & I_{3\times3} & -\left(C_b^n a^b \times\right) T \\ 0_{3\times3} & 0_{3\times3} & I_{3\times3} \end{bmatrix}_k \tag{18}$$

$$G_k = \begin{bmatrix} 0_{3\times3} & C_b^n T^2/2 \\ 0_{3\times3} & C_b^n T \\ C_b^n & 0_{3\times3} \end{bmatrix}_k \tag{19}$$

According to the characteristic that the velocity of SINS solution is the velocity error of positioning system in the static state of drill bit, the measurement equation of ZUPT for SINS of drill bit is constructed as follows,

$$V_k^n = H_{ZUPT,k} x_k + v_k \tag{20}$$

where, in Eq. (20),$H_{ZUPT,k} = [0_{3\times3} \quad I_{3\times3} \quad 0_{3\times3}]$, v_k is the SINS measurement noise.

Therefore, according to the state space equation composed of Eqs. (17) and (20) and combined with the static state detection algorithm, Kalman Filter algorithm is used to correct the drill bit SINS positioning process at zero speed, so as to improve the positioning accuracy of SINS.

D. RILLING BIT KC ALGORITHMS

The ZUPT strategy of SINS can be realized by using static state detection results during drilling stoppage, which can improve the positioning accuracy of SINS for drills. However, due to the large number of dynamic error sources in the actual positioning process, the conventional ZUPT strategy is limited by the time interval of drill stop, which makes it difficult to achieve in ideal positioning effect in the normal movement process. Therefore, when the bit is in motion, other algorithms are needed to correct the error.

According to the analysis above, it is known that the bit moves spirally along the working face under the constraint of screw, and its velocity has the constraint characteristics. Therefore, using the velocity constraint characteristics in the process of drilling motion, the SINS ZUPT algorithm is assisted to realize the strategy of drill SINS ZUPT assisted by the velocity constraint.

Firstly, the bit coordinate system is defined as the rectangular coordinate system fixed on the screw, whose three coordinate axes point to the forward, lateral and vertical direction of the bit respectively. At the same time, SINS is installed near the bit. Because of the problem of installation method and accuracy of SINS, there is an installation deflection angle between the bit coordinate system and the SINS carrier coordinate system. The deflection angle vector is expressed as $\beta^m = [\beta_x^m \beta_y^m \beta_z^m]$.Therefore, the velocity V_m of the bit in the coordinate system can be expressed as follows,

$$V^m = C_b^m C_n^b V^n \tag{21}$$

where, in Eq. (21), C_b^m is the attitude transformation matrix from the carrier coordinate system to the body coordinate system.

The total differential of Eq. (21) can be obtained as follows,

$$\delta \boldsymbol{V}^m = \boldsymbol{C}_b^m \left(\boldsymbol{C}_n^b \delta \boldsymbol{A} \times \boldsymbol{V}^n + \boldsymbol{C}_n^b \delta \boldsymbol{V}^n\right) + \delta \boldsymbol{\beta}^m \times \boldsymbol{C}_b^m \boldsymbol{C}_n^b \boldsymbol{V}^n \quad (22)$$

where, in Eq. (22), $\delta \boldsymbol{\beta}^m$ is the installation angle error vector of SINS in the bit.

The state vector of drill SINS in motion is extended to $\boldsymbol{x}_{s,k} = [\boldsymbol{x}_k^T \delta \boldsymbol{\beta}^b]^T$. Because SINS is fixed on the screw, the installation error angle vector does not change with the time of measurement in the process of bit positioning. Therefore, it is obtained as follows,

$$\delta \boldsymbol{\beta}_{k+1}^m = \delta \boldsymbol{\beta}_k^m + \boldsymbol{w}_{\beta,k} \quad (23)$$

where, in Eq. (24), $\boldsymbol{w}_{\beta,k}$ is the transmission noise of SINS installation error angle, which is zero mean Gauss white noise. According to the equation of state of Eq. (16), the equation of state after adding the installation error angle vector can be obtained as follows,+

$$\underbrace{\begin{bmatrix} \boldsymbol{x}_{k+1} \\ \delta \beta_{k+1}^m \end{bmatrix}}_{\boldsymbol{x}_{s,k+1}} = \underbrace{\begin{bmatrix} \boldsymbol{F}_{k,k+1} & 0_{9\times 3} \\ \boldsymbol{0} & \boldsymbol{1} \end{bmatrix}}_{\boldsymbol{F}_{s,k,k+1}} \underbrace{\begin{bmatrix} \boldsymbol{x}_{k+1} \\ \delta \beta_{k+1}^m \end{bmatrix}}_{\boldsymbol{x}_{s,k}} + \underbrace{\begin{bmatrix} \boldsymbol{G}_k & 0_{9\times 3} \\ 0_{3\times 9} & \boldsymbol{I}_{3\times 3} \end{bmatrix}}_{\boldsymbol{G}_{s,k}} \underbrace{\begin{bmatrix} \boldsymbol{W}_k \\ w_{\beta,k} \end{bmatrix}}_{\boldsymbol{w}_{s,k}} \quad (24)$$

According to Eq. (22), the SINS measurement equation under the constraint of bit kinematics is obtained as follows,

$$\underbrace{\begin{bmatrix} \boldsymbol{V}_x^m \\ \boldsymbol{V}_z^m \end{bmatrix}}_{\boldsymbol{V}_{M,C,K}^m} = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} [0_{3\times 3} \quad \boldsymbol{C}_b^m \boldsymbol{C}_n^b - \boldsymbol{C}_b^m \boldsymbol{C}_n^b (\boldsymbol{V}^n \times) \quad (-(\boldsymbol{C}_b^m \boldsymbol{V}^b)\times)]}_{\boldsymbol{H}_{M,C,K}} \times \boldsymbol{x}_{s,k} + \boldsymbol{v}_{v^m,k} \quad (25)$$

where, in Eq. (25), $\boldsymbol{v}_{v^m,k}$ is the noise of the motion constraint measurement equation and $\boldsymbol{V}_{KC,k}^m$ is the lateral and longitudinal velocity components of the bit under the kinematics constraint.

Combining SINS positioning measurement equation based on ZUPT and SINS measurement equation under KC, the overall system measurement equation is obtained as follows,

$$\begin{cases} \boldsymbol{V}_k^n = \boldsymbol{H}_{ZUPT,k} \boldsymbol{x}_k + \boldsymbol{v}_k, & C_{m,k} = 1 \\ \boldsymbol{V}_{MC,k}^n = \boldsymbol{H}_{MC,k} x_{s,k} + \boldsymbol{v}_{v^m,k}, & C_{m,k} = 0 \end{cases} \quad (26)$$

By judging the static state of the bit, the ZUPT strategy and KC strategy of SINS can be automatically switched, and then the cumulative error of SINS can be corrected effectively, and the positioning accuracy of the bit can be improved. The SINS cumulative error correction model of bit under different conditions is shown in Figure 4.

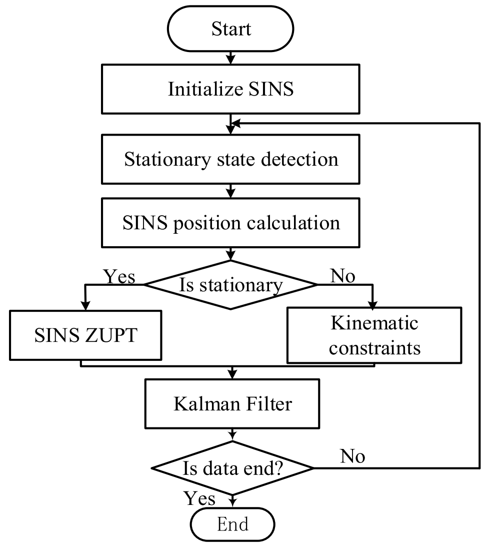


FIGURE 4. Selection of SINS measurement error correction model for different bit states.

FIGURE 5. Experimental scene of measuring while drilling.

IV. EXPERIMENTAL RESEARCH

A. CONSTRUCTION OF THE EXPERIMENTAL PLATFORM

This experiment completes the experimental verification of the theory proposed in this paper by building a complete experimental platform for measuring while drilling. The platform is built as showed in Figure 5. The measuring device while drilling is integrated above the drill bit. The measured data are transmitted to the computer on the ground in real time by wireless mode during the experimental drilling process. The experimental data are analyzed by the computer's measuring MWD system, and the final experimental results are formed.

In the experiment, the SINS in the MWD system adopts six-degree-of-freedom SINS ADIS16350, which consists of three-axis accelerometer and three-axis gyroscope. The system uses RS232 serial data transmission to transmit the measurement data to the upper computer. The baud rate of SINS system is 115200 bit/s, the sampling period is 0.01 s, the attitude reference accuracy of SINS is 10'', and the measurement resolution of acceleration is 2×10^{-5} G. The Bluetooth serial module WE-40 is used to support time-sharing one-to-many communication. The maximum transmission baud rate is 1382400 bit/s and the maximum communication distance is 100 m. The stable and efficient transmission of data can be realized. Therefore, the method has real-time performance and no delay. After data transmission to the ground system, the bit trajectory can be quickly calculated.

B. EXPERIMENTAL RESULT

During the experiment, three-axis acceleration and tri-axial angular velocity of the bit are measured by MWD system. After decomposition and reconstruction of the signal while drilling, they are substituted into the ZUPT SINS positioning model based on kinematics constraints, and the calculation results of the bit positioning model are obtained.

Firstly, the signal while drilling is decomposed according to Eq. (1), Because of the advantage of EMD, the original data are decomposed to obtain the IMF and residual components with frequencies from high to low. According to Eq. (2), the autocorrelation function of each order IMF component is calculated. According to the characteristic, that the maximum value of noise autocorrelation function at zero is very small elsewhere, the dominant noise component is judged. Eq. (3) is used to de-noise the main IMF component by using wavelet packet de-noising method. In this paper, the main IMF component is decomposed into three layers using db3 wavelet, and eight different frequency bands are obtained. Then, the optimal wavelet basis is obtained according to the Shannon entropy criterion. The coefficient is quantified by soft threshold, and finally reconstructed. The main IMF component and the remaining IMF component after de-noising are reconstructed to obtain the measured signal while drilling after de-noising.

The results of the signal before decomposition and reconstructed are shown in Figure 6 and Figure 7. By comparing the two diagrams, it is obvious that after processing the signal while drilling with this method, the useful signal and noise can be separated very well, which not only retains the effective characteristic components of the signal, but also restrains the noise, and effectively improves the accuracy of the signal while drilling.

The static state of the bit is judged by the reconstructed signal of the MWD system after de-noising. According to the acceleration and angular velocity information of SINS, the static time of the bit in motion is calculated by setting the threshold judgment algorithm of the static state. Result of SINS static state judgment is showed in Figure 8. The first and second sub-graphs are A_1 and A_2 calculated by acceleration and angular velocity of Eq. (5) and Eq. (6) respectively. The third sub-graph is obtained by Eq. (7) It is observed that the static state judgments by the model can reflect the static state of the bit during down-hole drilling steadily and effectively, which is SINS after drilling. The positioning solution has laid a good foundation.

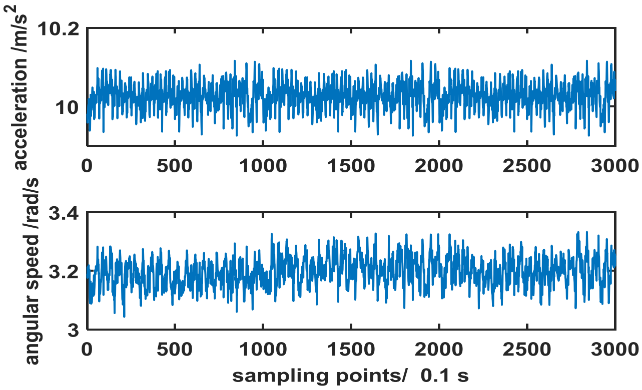


FIGURE 6. Original tri-axial signal while drilling.

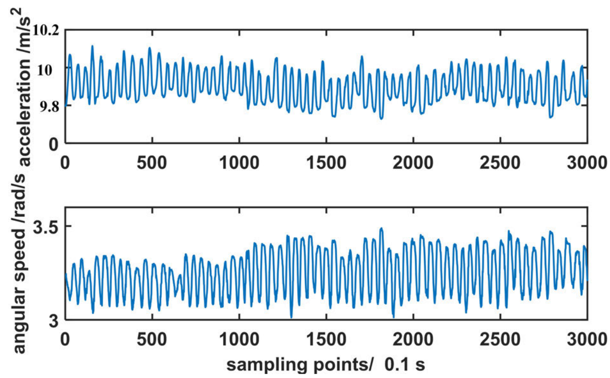


FIGURE 7. The reconstructed signal after de-noising.

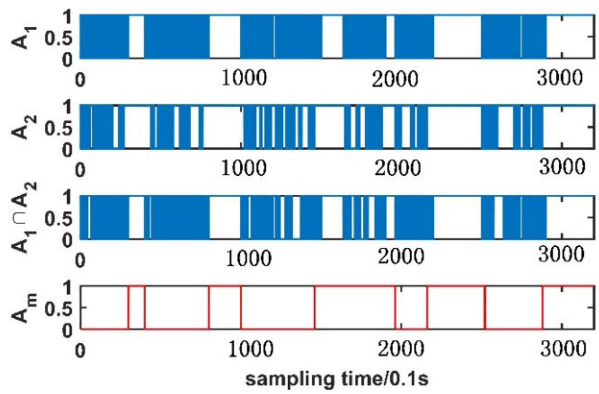


FIGURE 8. Static judgment result of drilling bit.

Based on the judgment result of SINS static state, the attitude angle of three axes of SINS is calculated by using quaternion attitude calculation model Eq. (9). After obtaining

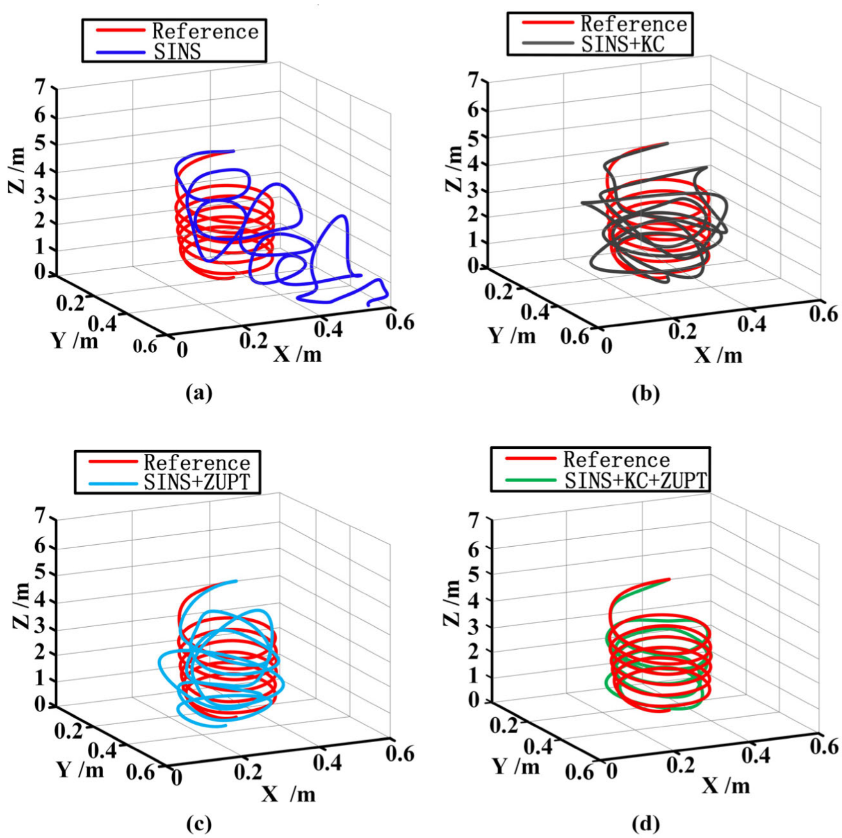


FIGURE 9. Drilling Bit positioning results with different correction methods.

the attitude angle of the bit at different time, the attitude of the bit is calculated by using Eqs. (10), (11) and (12).

After the attitude calculation of SINS, the positioning results of SINS are optimized and calibrated according to the speed and position calculation model of SINS in Section III, combined with the KC model and ZUPT algorithm proposed in this study. Firstly, acceleration and angular velocity information obtained from SINS measurement are used to calculate the pure SINS solution under static state measurement deviation correction, and the measurement deviation correction under KC is carried out by using the motion characteristics of drill bit. Results of pure SINS positioning and KC are shown in the Figure 9a. From the Figure 9, the result of SINS-only positioning calculation has serious cumulative errors since in the beginning, and its positioning trajectory deviates from the reference trajectory represented by the red solid line. After correcting the KC of the SINS solution model based on Kalman Filter, the calculation result is shown in the gray curve in the Figure 9b. It can be seen that the positioning trajectory corrected by KC can basically follow the direction of the reference trajectory in the direction of motion, and the divergence of the reference trajectory is smaller than that of the positioning trajectory calculated by pure SINS. However, since the KC algorithm belongs to the nonholonomic constraint, its location trajectory also diverges to a certain extent after the start of positioning.

In the process of drilling, it is inevitable that the bit will stop in the middle. Because of the existence of measurement error and attitude calculation error, the speed of SINS will not decrease to zero during the static process of the bit. This leads to that although the bit is in the static state, the positioning trajectory of SINS is still in the moving state. Therefore, large drift error accumulation will occur, which seriously affects the positioning accuracy of SINS. According to the static state detection model mentioned in Section III and the ZUPT strategy, the ZUPT experiment is carried out on the basis of the zero-speed state detection mode. Experimental positioning results based on SINS ZUPT are shown in the Figure 9c. As shown, the SINS positioning trajectory after ZUPT is closer to the reference trajectory set by the experiment than that without ZUPT. Because the ZUPT strategy based on Kalman Filter can effectively suppress the velocity drift error during the static period of the bit, the divergence of SINS positioning trajectory was suppressed. From Figure 9c the ZUPT velocity can be reduced to the state of near zero-speed when the static state occurs in the course of motion, thus reducing the influence of accumulated velocity errors on the positioning results.

Based on KC model and ZUPT algorithm, the positioning accuracy of down-hole drill is improved obviously. Therefore, this paper proposes an assistant positioning strategy of down-hole drill motion constraint, which makes the alternation of KC model and ZUPT model in the process of drilling motion and stop, and further improves the positioning accuracy of SINS. The experimental results is showed in Figure 9d.

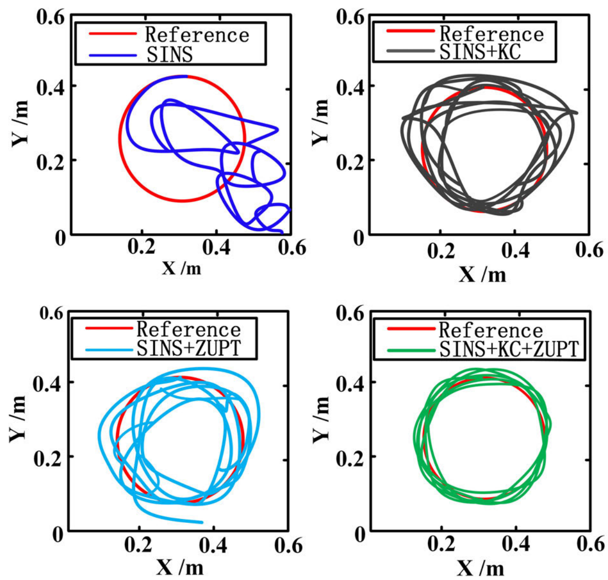


FIGURE 10. **Drilling bit positioning and overlooking with different correction methods.**

In order to more intuitively compare the positioning accuracy of different models, Figure 10. is the top view of bit trajectory, and Figure 11. is the deviation comparison between the position of three axes and the reference position. From the Figure 11, all the pure SINS three axes have obvious drift phenomenon, and the positioning trajectory calculated by simple SINS cannot follow the direction of the reference trajectory in the direction of movement, and its positioning process can not follow the direction of the reference trajectory. The maximum position error is about 2.1 m. KC model and ZUPT algorithm have an obvious effect on drift suppression. The maximum positioning error of positioning trajectory under KC is about 0.65 m, which is 68.9% higher than that of pure SINS algorithm. The maximum positioning error of positioning trajectory under ZUPT is about 0.74 m, which is 64.7% higher than that of pure SINS algorithm. The accuracy of head positioning is 92.6%. At this time, the maximum positioning error is increased to 0.15 m compared with the pure SINS algorithm.

In order to validate the stability of the SINS model proposed in this paper, drilling depth and experimental time will continue to be enlarged. The simulated drilling depth is 10 m. The bit speed is slowed down and drilling time is prolonged up to 1500 s. The experimental results are shown in Figure 12. By comparing the corrected curve with the reference red datum curve, the positioning accuracy of the bit is 90.2%, and the maximum positioning error is 0.31 m. From the comparison results, the proposed auxiliary positioning strategy based on the motion constraint of down-hole bit MWD system is effective. The trajectory of the center of gravity of the drill pipe is shown in Figure 13. The trajectory of the center of gravity of the pure SINS drill pipe without model correction is seriously offset in Figure 13. And the migration is obviously suppressed after model correction.

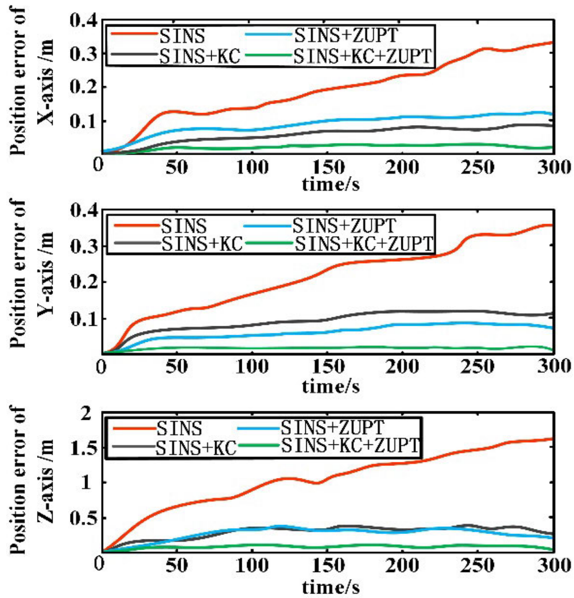


FIGURE 11. **Position error of SINS with different correction methods.**

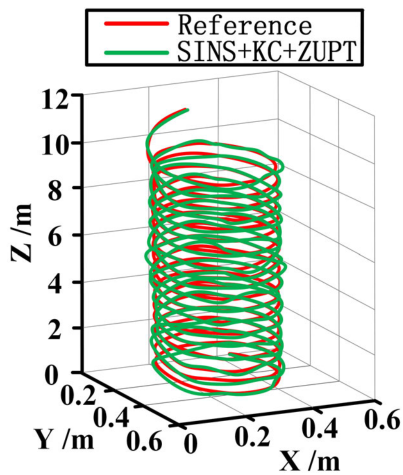


FIGURE 12. **Experimental results of drilling bit positioning for 10 meters.**

By analyzing the experimental data of drilling depth up to 10 m, the precise comparison results of bit trajectories under different models are obtained, as showed in Table 1. Based on this table, SINS using KC aided ZUPT model can effectively suppress the cumulative error of SINS and has high positioning accuracy.

TABLE 1. Performance comparison for different integration models.

Item	Axis	SINS	SINS+KC	SINS+ZUPT	SINS+KC+ZUPT
Absolute value range of position error (m)	x	0 to 0.832	0 to 0.212	0 to 0.279	0 to 0.079
	y	0 to 0.625	0 to 0.184	0 to 0.212	0 to 0.058
	z	0 to 5.148	0 to 1.665	0 to 1.791	0 to 0.473
Variance	x	3.113	0.914	1.167	0.082
	y	2.786	0.855	0.973	0.064
	z	19.329	5.129	4.256	0.482
Maximum position error (m)		7.728	1.885	2.172	0.512
Average value of position error (m)		5.354	1.223	1.657	0.354

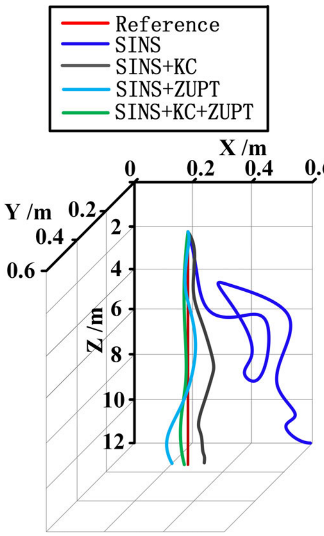


FIGURE 13. Center of gravity trajectory of drilling pipe with different correction methods.

V. CONCLUSION

Aiming at the problem that drilling bit cannot be positioned accurately in real time during drilling, the measurement characteristics of strap-down inertial navigation accelerometer and gyroscope in MWD system are analyzed, and an EMD wavelet de-noising algorithm based on measurement limit while drilling is proposed. On the basis of engineering and theory, an alternating action model of ZUPT strategy for KC model of drilling bit is established. It effectively improves the positioning accuracy of the bit in the down-hole drilling process.

In order to verify the effectiveness of the proposed method, simulation drilling is used to verify the proposed positioning error correction strategy. The experimental results show that during the 300 s experiment, the positioning results calculated by SINS alone have large positioning errors since the beginning of the experiment, and the positioning errors continue to increase with the lapse of the positioning time, with the maximum positioning error reaching 2.1 m. KC algorithm and ZUPT model have obvious influence on drift suppression. The maximum positioning error of KC is about 0.65m, which is 68.9% higher than pure SINS algorithm. The maximum positioning error of the positioning trajectory under ZUPT is about 0.74m, which is 64.7% higher than that of SINS. When the two models work together, the maximum positioning error of the bit is 0.15m and the accuracy is 92.6%. In order to verify the accuracy of the proposed method, the drilling depth and experimental time are expanded. The experimental results show that the positioning accuracy of the bit is 90.2% at the drilling depth of 10 m and the drilling time of 1500 s. From the experimental results, it can be concluded that the proposed assistant positioning strategy based on the motion constraint of down-hole bit while drilling measurement system has obvious effect, and the accuracy of down-hole bit positioning has been greatly improved, which provides an effective theoretical basis and technical support for subsequent down-hole positioning research.

VARIABLE ANNOTATION TABLE

$x(t)$	Original While Drilling Measurement Signal
$c_i(t)$	IMF Components with Different Frequency Band Scales
$r_n(t)$	Residual Components of Decomposed Signals
$x_{corr}(\tau)$	Autocorrelation Function
imf_{k}	Modal Components with Noise
$\|\boldsymbol{a}_k^b\|$	Acceleration in SINS Carrier Coordinate System
$\left\|\boldsymbol{w}_{ib,k}^b\right\|$	Angular Velocity in SINS Carrier Coordinate System
A_1	Acceleration Static State Judgment Result
A_2	Angular Velocity Static State Judgment Result
$A_{m,i}$	Static State Judgment Results after Median Filtering
$S_{a,max}$, $S_{a,min}$	Static State Judgment Threshold of SINS Acceleration
S_w	Static State Judgment Threshold of SINS Angular Velocity
$\boldsymbol{C}_b^n$	Attitude Transformation Matrix from Carrier Coordinate System to Navigation Coordinate System

$\boldsymbol{C}_n^b$	Attitude Transformation Matrix from Navigation Coordinate System to Carrier Coordinate System
Ψ	Drilling Bit Heading Angle
θ	Drilling Bit Pitch Angle
γ	Drilling Bit Roll Angle
$\boldsymbol{a}_k^n$	Acceleration Vector in Navigation Coordinate System
V_k^n	Velocity Vector in Navigation Coordinate System
p_k^n	Position Vector in Navigation Coordinate System
$\boldsymbol{g}^n$	Gravity Acceleration Vector of Bit Location
$\boldsymbol{V}_k^n$	Velocity Vector in Bit Navigation Coordinate System
$\boldsymbol{P}_k^n$	Position Vector in Bit Navigation Coordinate System
$\boldsymbol{\delta P}^n$	Position Error Vector in Bit Navigation Coordinate System
$\boldsymbol{\delta V}^n$	Velocity Error Vector in Bit Navigation Coordinate System
$\boldsymbol{\delta A}$	Drilling Bit Attitude Error Vector
$\boldsymbol{\delta a^b}$	Measurement Noise of SINS Accelerometer
$\boldsymbol{W}_k$	System Noise Vector of State Equation
$\boldsymbol{F}_{k,k+1}$	One step Transfer Matrix of State Vector
$\boldsymbol{G}_k$	One Step Transfer Matrix of System Noise
$\boldsymbol{H}_{ZUPT,k}$	SINS Zero Speed Correction Measurement Matrix
$\boldsymbol{C}_b^m$	Attitude Transformation Matrix from Carrier Coordinate System to Body Coordinate System
$\boldsymbol{V}_{KC,k}^m$	Lateral and Longitudinal Velocity Components of Bits under Kinematic Constraints
$\boldsymbol{v}_{v^m,k}$	Noise of Kinematic Constrained Measurement Equation
$\boldsymbol{V}^m$	Velocity Vector of Bit in Drilling Tool Coordinate System

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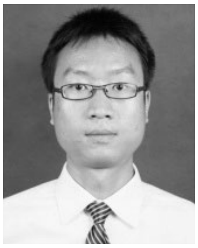

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