Error Analysis in Accelerometers Calibration of Measurement while Drilling Instrument used in Directional Drilling Operations

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Abstract The aim of this paper is to analyze the sensor errors in measurement while drilling (MWD) instrument used in directional drilling operations. The MWD consist of three orthogonal accelerometers, three orthogonal magnetometers and one temperature sensor. The system formulation is achieved through the system analysis and functional consideration. The obtained formulation is validated and verified by comparing the results obtained from measurements and simulations. The accelerometers calibration, to estimate bias factors, scale factors and non-orthogonal factors of sensors, is done using optimal non-linear Newton Raphson algorithm by considering the high temperature calibration coefficients. The accuracy of the experimental results, obtained from several measurement while drilling systems in Iranian national oil drilling company shows the effectiveness of the approach.

Keywords: Directional drilling, Measurement While Drilling Instrument, Calibration, Sensor data fusion, Bias, Scale factor, Non-orthogonality

1. Introduction

Directional or deviational drilling refers to a certain type of drilling in which the upper part of the reservoir at ground level is not accessible due to housing or its impassability. Therefore, drilling begins from adjacent areas and, after a certain amount of drilling, directional drilling starts using a cut in the casing and continues to the intended point [1].

Deviated and horizontal drilling were first used in drilling oil well No.18 at the airport in Ahvaz city in Iran, in ۱۹۹٤. Due to the rapid spread of this technology in the oil industry and the urgent need for this type of drilling, operational knowledge and scientific independence in this field are necessary.

Directional drilling is very appropriate in the mountains, seas and urban areas. There is a fundamental problem with this requiring accurate measurement for having precise location of different tools and knowing the position of well. To achieve that, calculating parameters such as Inclination and Azimuth need to be not only accurate, but also stable, high temperature resistant, shock resistant, and so on [2].

Nowadays, inclinometer devices are used in many applications such as attitude navigation system, mobile cell phones, robot navigation control, human action monitoring, machine vision, oil and gas well directional drilling. In well directional drilling, measurement while drilling (MWD) is used to obtain the related parameters.

Many studies were conducted on Inclination and Azimuth measurement systems based on the type of application. For instance, robot control [3], positioning navigation systems [4, 5], monitoring of human movement [6, 7] and in directional drilling [8] can be noted.

Inertial sensors exhibit biases, scale factor variations, axis nonorthogonalities, drifts, and noise characteristics. These errors build up over time, corrupting the precision of the measurements. Therefore, it is important for sensors calibration to properly remove these errors before the start of navigation [9]. In specific applications such as oil or gas directional drilling, the measurements have to be accurate, stable and resistant to heat and shock.

Zhu et al. [10] suggested an Azimuth level detector with the installation of non-orthogonal error analysis and compensation of this error. Husak et al. [11] proposed a smart sensor system for calculating the Tilt by measuring the horizontal plane offered in two axes. Ang et al. [12] studied a nonlinear regression model to reduce certain errors associated with bias, scale factor and misalignment disclosure. Luczak et al. [13] considered the problem of nonlinear part in Tilt measurement. Leavitt et al. [14] used a linear time invariant system to accurately measure the angle using low-cost sensors of accelerometers, gyro and a second order model.

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Parsa et al. [15] applied least squares method to calibrate the errors of accelerometer axes misalignment. Frosio et al. [16] proposed a 9-parameter model for calibration of MEMS accelerometers in which the model parameters estimated by iterative method. Qian et al. [17] provided a linear model for accurate measurements of Tilt and parameter estimation using the least squares method.

In all the above-stated articles, the temperature calibration coefficients have ignored. This is what we have to bear in mind. In this paper we analyze the sensor errors in measurement while drilling (MWD) instrument used in directional drilling operations. The MWD consist of three orthogonal accelerometers, three orthogonal magnetometers and one temperature sensor.

The system formulation will be achieved and the system calibration will be done using optimal non-linear Newton Raphson algorithm. The accuracy of the experimental results shows the effectiveness of the system calibration.

This paper is organized as follows: Section 2 contains the description of the sensor model and directional drilling; section 3 demonstrates Faults and errors in directional drilling sensors and illustrates the solution to calibrating the accelerometers; section 4 contains the experimental results. Discussion and conclusion are drawn in section 5.

2. Directional drilling and Required Parameters

Directional drilling, as a solution to difficult problems and achievement of complex reservoirs, is welcomed by drilling companies and also clients. Today, given the high costs of manufacturing, mining, oil and gas flowing, directional drilling is a necessity (Fig.1). The most important characteristic of this technique is that it enables manufacturers to use reservoirs that economically is not possible to extract them by any other method**.**

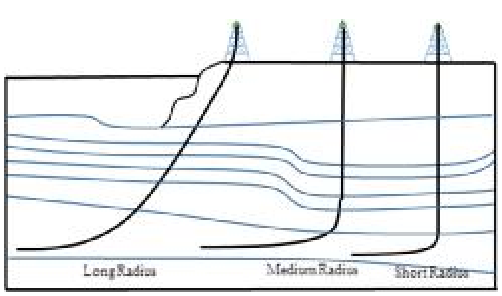

Figure1. Several types of directional drilling

2.1. Application of Directional Drilling

Deviation from the original route is the most important reason for directional drilling. The purpose is to circumvent or bypass the left parts in the well. When the reservoir or drilling target is located under a city, river or a route that is environmentally sensitive, it is necessary to put the drilling machine in a place away from it. In the case, by drilling a well we can access the target.
Sometimes oil reservoirs seen below the salt domes that cap stones. Many problems are associated with drilling inside salt layers. One solution to avoiding these problems is the use of directional drilling and avoiding entering the salt layer. Sometimes wells that have been drilled vertically become tilt. This phenomenon is usually due to a fault in the subsurface layers. Usually it is better that a directional wells to be drilled and dealing with faults to be avoided. A new well can be drilled by blocking the wells at a certain depth and creating a deviation. Mouth of a well can be used as a point of branching for other wells. This allows for exploration and investigation of subsurface layers without having to drill several wells completely. By installing the mast on land and directional drilling of wells, accessed in to the reservoirs located beneath the water surface will be possible. By doing this, while wellhead valves can be installed on land, it would be possible to avoid high drilling costs in the sea. Directional drilling , from a marine platform to multilateral wells , is one of the most economic ways to develop an offshore field [١] .

2.2. Required parameters

The first consideration for directional drilling is that it requires an accurate design and measurement for accurate positioning of tools and knowing the position of well. To achieve this objective, some parameters must be measured.
Currently, in the world of drilling industry a variety of measurements while drilling tools (MWD) are used. Iran National Drilling Company is equipped with a negative pulse type system of directional drilling (Fig.2) which operates in the well equipped with sensors, acceleration sensors and Magnets Gauge for special measurements. Then, during a process by a pulse producer toll, data are sent without cable and by leaving mud (through a route other than the drilling embedded in pulser), over a certain distance by orders from

the bottom to the surface. The data sent to the surface, created due to the pressure in the drilling string on the surface, are converted to electrical current by a pressure transducer and converted into to the processor. Finally, it will be sent to the computer and drilling screens will represent a variety of graphs required for the drilling experts to control the well route.

Figure 2. Measurement while drilling instrument (in courtesy of NIDC)

Some of these parameters are:

A.) Inclination or Tilt, or the angle between earth's gravity and axis Z that vertically represents deviation along the well (Fig.3). This quantity is an angle range from 0 to 180 degrees. Vertical direction is considered as gravitational acceleration (g) that is a radius vector directing to the center of the earth.

B) Azimuth or directional angle represents the deviation amount of well image on the horizontal plane (the page that is perpendicular to g) to the north - south magnetic field (Fig.3). This quantity is the angle ranging from 0 to 360 ° .

C) The actual depth of well measured by devices which are at surface with respect to piping and Inclination, Azimuth angles and length of tools. In fact, the depth of wells is represented in two ways:

1) drilled area that is the same as deviation well; of course it is not the same as the depth of wells (distance of endpoints with the ground). Usually, it is called measured depth (MD).

2) The real depth of the well is approximately calculated by knowing Inclination and Azimuth angles.

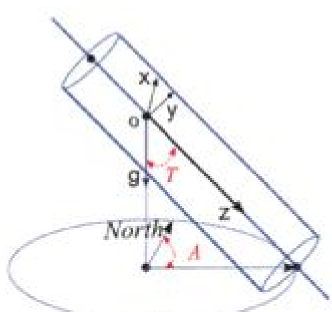

Figure 3. Tilt and azimuth angles [2]

D) Magnetic Azimuth Measurement: It is the angle between the vertical plane passing through the wells axes and the vertical plane passing through north magnetic. This is measured by a magnetic needle or by a floating compass that points towards the Earth's magnetic flow. It can be measured by a magnetometer that measures three images of magnetic field vector.

By having components of vector g on three axes, the following values can be calculated:

A – Acceleration angle of gravity with each axis. Since one axis is aligned with the tool, then the tool and the well are the same. So inclination angle can be calculated.

B – Rotation of tool around itself to a certain point on the tool (this quantity is an angle ranging between 0 - 360 degrees that is very important in directional drilling). This quantity is called tool face used to determine the bit face.

Measuring rotation of tool around itself, which eventually is used to calculate the tool face, using acceleration sensors gauge, is limited. Because of in case of low deviation value, the measured value is of low accuracy. That is why in these cases magnetometer sensors are used to calculate the rotation. Magnetometer sensors are not working properly in the hardware environment (unusual mode of environmental earth's magnetic field caused by the presence of iron compounds). Therefore, a part of drilling string as a location for directing sensors are covered with non-magnetic pipes (Manel) for properly function of magnetometer sensors.

2.3. Faults and errors in directional drilling sensors

With field surveys and personal observations made in Iran National Drilling Company as well as meetings with experts of drilling, it was determined that, in addition to primary source of errors caused by sensors or improper installation of error, in the drilling operation, some errors occur due to other causes. Some of which are as follows:

Impacts during drilling operations

Impact of drill, due to its hardness, generally cause failure of at least one of the sensors or cause error of non- orthogonal sensors.

Impacts due to efforts to free the drill pipe

For various reasons, drill pipe stuck in the earth layers in wells and for their release usually a tool called JAR is used to create a huge blow to free pipes. Severity of the impact is to the extent that, despite the depth of several thousand meters of well, it can be felt on the ground too. It generally causes the failure of at least one of the sensors.

Heat

In well drilling, the earth's interior temperature reaches about 130 °. This high temperatures and temperature changes cause changes in the earth's surface to a depth of wells bias and scale factor and sometimes a sudden rise in temperature causes the breakdown of several sensors.

Inner earth layers and magnetic materials

The existence of materials with magnetic effects such as metals, iron and its alloys or remains of previous drilling or protecting Manel Improperly cause changes in the sensor bias and scale factor.

Drilling within other wells

In case of drilling operations and within other wells, especially in the sea, the pipes wall cause malfunctions of sensors. This usually causes a change in bias sensor or their scale factor.

Consecutive sensors on and off

Considering the use of certain battery power and the need to save energy for a long time during drilling and the impossibility of replacing the batteries and also high energy consumption by sensors, systems design sample is that gets on only when receives the order of operation of sensors and sampling performs. In other cases, the sensors are turned off with no power consumption.

2.4. Modelling

In the current directional drilling tool, seven sensors are used, three orthogonal structure accelerometer, three orthogonal structure magnetometer and one temperature sensor. By studying the available catalogs and full review of available hard ware and software in the current system, the following model was obtained for the sensors.

SF_A^* *Full scale factor and* B_A^* *Full bias* of accelerometer sensor A obtained from equations (1) and (2). For each of the other accelerometer and magnetometer sensors, similar coefficients of accelerometer sensor A are defined.

$$SF_A^* = SF_A + SFT1_A(T_S - T_C)^1 + SFT2_A(T_S - T_C)^2 + SFT3_A(T_S - T_C)^3 \quad (1)$$

$$B_A^* = B_A + BT1_A(T_S - T_C)^1 + BT2_A(T_S - T_C)^2 + BT3_A(T_S - T_C)^3 \quad (2)$$

Parameters used in the equations are:

A, B, C : Accelerometers with an orthogonal structure

T_s : The temperature measured by a temperature sensor

T_C : Nominal temperature, usually 30°C

SF_A : Scale factor, acceleration sensor temperature - independent A

$SFT1_A$: First order scale factor, acceleration sensor temperature-dependent A

$SFT2_A$: Second order scale factor, acceleration sensor temperature-dependent A

$SFT3_A$: Third order scale factor, acceleration sensor temperature-dependent A

B_A : Independent bias of the temperature acceleration sensor A

$BT1_A$: First-order temperature-dependent bias acceleration sensor A

$BT2_A$: Second-order temperature-dependent bias acceleration sensor A

$BT3_A$: Third-order temperature-dependent bias acceleration sensor A

Equations (3) to (8) were obtained to calculate the gravitational acceleration and intensity of earth's magnetic field in line with each following sensors.

$$G_A = \left(\frac{V_A}{SF_A^*} - B_A^*\right) - m_{AB}\left(\frac{V_B}{SF_B^*} - B_B^*\right) - m_{AC}\left(\frac{V_C}{SF_C^*} - B_C^*\right) \quad (3)$$

$$G_B = \left(\frac{V_B}{SF_B^*} - B_B^*\right) - m_{BA}\left(\frac{V_A}{SF_A^*} - B_A^*\right) - m_{BC}\left(\frac{V_C}{SF_C^*} - B_C^*\right) \quad (4)$$

$$G_C = -\left(\frac{V_C}{SF_c^*} - B_C^*\right) + m_{CA}\left(\frac{V_A}{SF_A^*} - B_A^*\right) + m_{CB}\left(\frac{V_B}{SF_B^*} - B_B^*\right) \quad (5)$$

$$H_X = \left(\frac{V_X}{SF_X^*} - B_X^*\right) - m_{XY}\left(\frac{V_Y}{SF_Y^*} - B_Y^*\right) - m_{XZ}\left(\frac{V_Z}{SF_Z^*} - B_Z^*\right) \quad (6)$$

$$H_Y = \left(\frac{V_Y}{SF_Y^*} - B_Y^*\right) - m_{YX}\left(\frac{V_X}{SF_X^*} - B_X^*\right) - m_{YZ}\left(\frac{V_Z}{SF_Z^*} - B_Z^*\right) \quad (7)$$

$$H_Z = \left(\frac{V_Z}{SF_Z^*} - B_Z^*\right) - m_{ZX}\left(\frac{V_X}{SF_X^*} - B_X^*\right) - m_{ZY}\left(\frac{V_Y}{SF_Y^*} - B_Y^*\right) \quad (8)$$

Where the parameters are:

V_A, V_B, V_C : The voltages of measuring accelerometers

X, Y, Z : Magnetometers with an orthogonal structure

V_X, V_Y, V_Z : The voltages of measuring magnetometers

G_A, G_B, G_C : The gravitational acceleration in each direction

H_X, H_Y, H_Z : Earth's magnetic field intensity in each direction

$$m_G = \begin{bmatrix} 0 & m_{AB} & m_{AC} \\ m_{BA} & 0 & m_{BC} \\ m_{CA} & m_{CB} & 0 \end{bmatrix}$$: Non-orthogonal coefficient matrix between acceleration sensors

$$m_H = \begin{bmatrix} 0 & m_{XY} & m_{XZ} \\ m_{YX} & 0 & m_{YZ} \\ m_{ZX} & m_{ZY} & 0 \end{bmatrix}$$: Non-orthogonal coefficient matrix between magnetic sensors

Accordingly, required parameters of drilling for drilling engineers are calculated based on equations (9) to (12).

$$G_L = \sqrt{G_A^2 + G_B^2 + G_C^2} \quad (9)$$

$$H_L = \sqrt{H_X^2 + H_Y^2 + H_Z^2} \quad (10)$$

$$Tilt = \tan^{-1}\left(\frac{\sqrt{G_A^2+G_B^2}}{G_C}\right) \quad (11)$$

$$Azi = \tan^{-1}\left(\frac{G_L(H_X G_B - H_Y G_A)}{G_C(H_X G_A - H_Y G_B) + H_Z(G_A^2 + G_B^2)}\right) \quad (12)$$

In this system, calibration means finding a total of 60 factors, including bias factors, scale factors and non-orthogonal factors of sensors.

In the directional drilling operating system for quality control testing of MWD system calibration in a certain angle (usually 45 degrees), the toll was turned around itself in 12 different rotation and following conditions were approved for quality control issue , If the results met the following conditions 13 to 15.

$$|Max(Inc) - Min(Inc)| < 0.1 \quad (13)$$

$$|Max(Azi) - Min(Azi)| < 1 \quad (14)$$

$$|Max(G_L) - Min(G_L)| < 0.003 \quad (15)$$

3. Calibration of accelerometers

Inclination angle and gravity acceleration are the major parameters for calibration. We define two errors e_{gk} and e_{Tk}. Error e_{gk} equals to the squared difference between the actual gravity acceleration and the total acceleration measured by accelerometers (16). Error e_{Tk} equals to the squared difference between the actual Inclination angle and the Tilt angle measured by accelerometers (17).

$$e_{gk} = G_{Ak}^2 + G_{Bk}^2 + G_{Ck}^2 - {G_L}^2 \quad (16)$$

$$e_{Tk} = \tan^{-1}\left(\frac{\sqrt{G_{Ak}^2+G_{Bk}^2}}{G_{Ck}}\right) - T_{actual} \quad (17)$$

To compute the model parameters of accelerometers, instrument is placed in N different orientations to evaluate the sensors output while maintaining it in a strictly static condition. By adding errors over all the measured orientation, cumulative errors are obtained as

$$E_g = \frac{\sum_{k=1}^{N} e_{gk}^2}{N} \quad (18)$$

$$E_T = \frac{\sum_{k=1}^{N} e_{Tk}^2}{N} \quad (19)$$

$$E = E_g + E_T \quad (20)$$

E is a nonlinear function of the sensor parameters. The parameters, which best fit the observation data in the least squares sense, can be determined by minimizing the cumulative error E with respect to the parameters. By using the initial values provided by accelerometer manufacturers, then using Newton-Raphson method [18], we start iterating. The iteration formula is as follows:

$$X^{t+1} = X^t - \alpha . H^{-1}(X^t) . J(X^t) \quad (21)$$

Where X^t is the unknown vector at the *t*th iteration, containing the sensors parameters, $J(X^t)$ and $H(X^t)$ are the Jacobian vector and the Hessian matrix of the error E, respectively. α is a damping parameter smaller than 1 and it is computed at each iteration by means of a line search procedure [18]. The iteration is terminated when the following convergence criterion is satisfied:

$$\max\left\{\left|\frac{x_k^n - x_k^{n-1}}{(x_k^n + x_k^{n-1})/2}\right|\right\}_{k=1,2,\ldots,30} < \varepsilon \quad (22)$$

Where x_k^n indicates the k^{th} element of X in n^{th} iteration, whereas ε is a threshold, which has been empirically set equal to 1.5×10^{-6} . Less than ten iterations are generally sufficient to convergence.

Using the method described above, the calibration is performed and Sensors coefficients are calculated.

4. Experimental results

In the experiment, for verifying the accuracy of our proposed model, we use MWD instruments (MWD123, MWD406 and MWD547 Tools of Iran National Drilling Company) (Fig. 4). We collect groups of tilt and azimuth sample data ($Tilt, Temp,\ V_A,\ V_B,\ V_C,\ G_A,\ G_B,\ G_C,$ $Azimuth, V_X, V_Y, V_Z, M_X, M_Y, M_Z$) to test the performance of our model. We gather several samples at several positions (at several tilts and azimuth angles). By using of equations 1 to 12, and comparing the tool measurements and our formulation simulated results it is showed that the obtained formulation is validated and verified. Computer simulation model with MATLAB and comparing the results with actual operational output of instruments represent the resulting model accuracy.

To evaluate the performance of calibration, we use MWD instrument (MWD123 Tool of Iran National Drilling Company). We collect groups of tilt sample data ($Tilt, Temp, V_A,\ V_B,\ V_C$) in two cases, first in the nominal temperature and second in different temperature from about $25℃\ to\ 80℃$. For The initial values of coefficients accelerometers, based on technical specifications provided by the manufacturer shown in Table 1.

Table1. Some of the most significant parameters of the JA5M36 Accelerometer[19]

Parameter	Value	Unit
Measurement range	± 4	G
Scale Factor (@25℃)	$3 \pm 5\%$	V
Bias(@25℃)	$\leq \pm 10$	mG
Axis Alignment	$\leq \pm 2$	Mrad
Noise	≤ 14	μA_{rms}
Scale Factor (Temp. Coeff.)	± 180 (max)	$ppm/_{℃}$
Bias (Temp. Coeff.)	± 100 (max)	$\mu G/_{℃}$

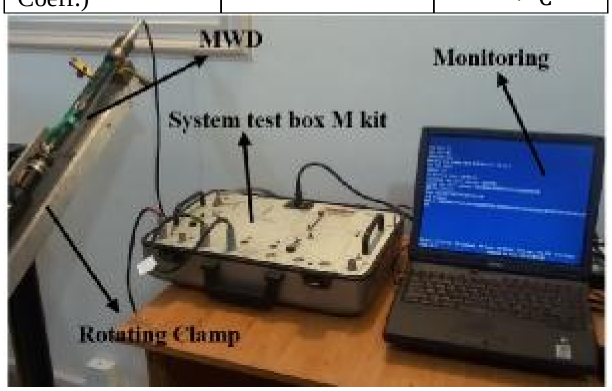

Figure 4. MWD instrument and calibration tools

4.1. 12 Parameters Calibration of MWD NIDC NO. 123

In this case groups of tilt sample data ($Tilt,\ V_A,\ V_B,\ V_C$) are collected in the nominal temperature (about 25℃). We gather several (typical 12) samples at a position (degrees $0, 45, 90, 135\ °$) by rotating tool around z-axis of the instrument. Then by using of calibration method illustrated above, the 12 nondependent temperature parameters are achieved. Figure 5 shows the error of Gravity calculation before and from calibration. This results in the case the error is nearly 0 after calibration. Figure 6 shows the error of Tilt angle calculation before and from calibration and it is seen that the Tilt error reduced to a large extent.

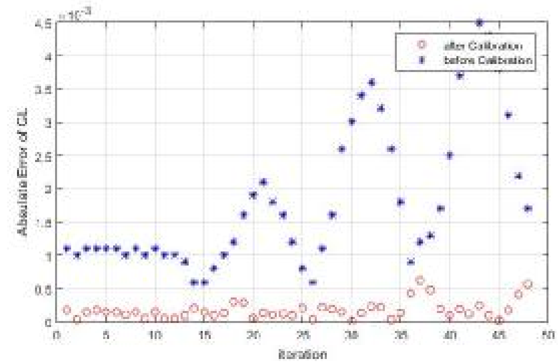

Figure 5. Absolute Error of GL, before and after 12 parameters calibration

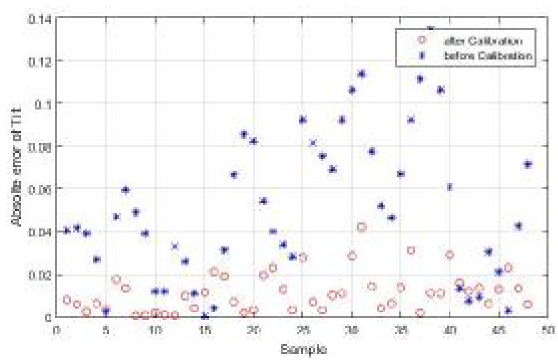

Figure 6. Absolute Error of Tilt angle, before and after 12 parameters calibration

4.2. 30 Parameters Calibration of MWD NIDC No. 123

In this case groups of tilt sample data ($Tilt, Temp, V_A,\ V_B,\ V_C$) are collected in the different temperatures (about $25℃\ to\ 80℃$). We gather several (typical 9) samples at a position ($degrees$: $0, 45, 90\ and\ 135\ °$) by rotating tool around z-axis of the instrument and the same time instrument temperature is changed by heater. Then by using calibration method illustrated above, the 12 nondependent temperature parameters and 18 dependent temperature parameters are achieved. Figure 7 shows the error of Gravity calculation before and from calibration. This results in the case the error is nearly 0 after calibration. Figure 8 shows the error of Tilt angle calculation before and from calibration and it is seen that the Tilt error reduced a large amount.

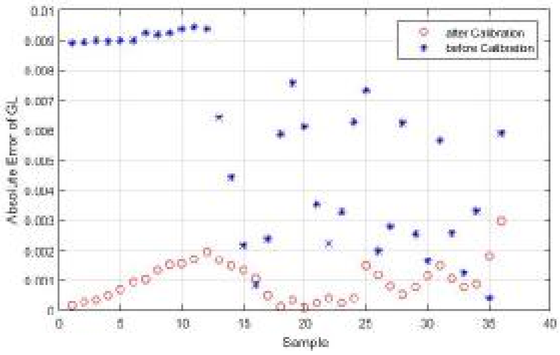

Figure 7. Absolute Error of GL, before and after 30 parameters calibration

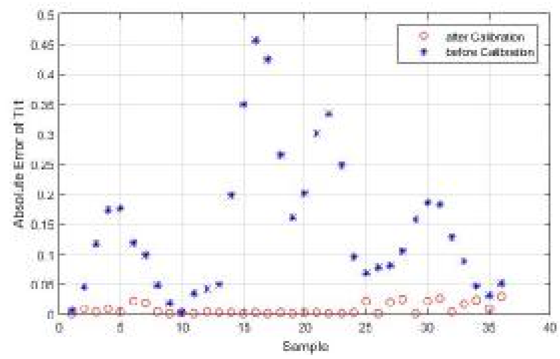

Figure 8. Absolute Error of Tilt angle, before and after 30 parameters calibration

5. Concusions

The system formulations of MWD consist of three orthogonal accelerometers, three orthogonal magnetometers and one temperature sensor through the system analysis and functional consideration is achieved. Validity and verification of the obtained formulation is illustrated by comparing the results obtained from measurements and simulations. The 30 parameters accelerometers calibration is done using optimal non-linear Newton Raphson algorithm by considering the high temperature calibration coefficients. The accuracy of the experimental results, obtained from several measurement while drilling systems in Iranian national oil drilling company, by calculating errors of Tilt and Total gravity before and after calibration shows that the effectiveness of the approach.

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